

CULTIVATING ENGINEERING LITERACY THROUGH A FIVE-STAGE UP-IDEA PEDAGOGICAL FRAMEWORK: EVIDENCE FROM A DIGITAL CIRCUIT COURSE REFORM

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Abstract: Engineering literacy cultivation in foundational engineering courses remains a persistent challenge in higher education. Traditional approaches often emphasize analytical proficiency over design competence and component knowledge over systems thinking. This study presents a pedagogical reform aimed at fostering engineering literacy through a five-stage Up-IDEA framework in a Digital Circuit and Logic Design course. The reform was implemented over three years with more than 2,000 students across 13 majors at Xi'an University of Posts and Telecommunications. The framework comprises five interdependent stages: Up (pre-class design submission), Inquiry (problem-driven classroom engagement), Design (software-based hardware design using Verilog HDL), Engineering (case-based practical application with engineering ethics integration), and Assess (multi-dimensional reflective evaluation). A quasi-experimental design was employed, triangulating learning platform analytics, questionnaire surveys, and institutional assessment data. Implementation yielded measurable improvements across three dimensions. Student engagement significantly increased, with class attendance reaching 98% and homework completion reaching 100%. Over 80% of students independently resolved more than 70% of pre-class learning problems, indicating enhanced autonomous learning capacity. Engineering practice outcomes showed 342 students receiving national or provincial awards in electronic design and FPGA competitions over three years. Comparative analysis with pre-reform cohorts indicated improvements in both student participation and design performance. The Up-IDEA framework provides a structured approach to integrating engineering literacy cultivation into foundational engineering courses. The closed-loop pedagogical cycle — connecting pre-class preparation, inquiry-based instruction, design-oriented learning, practical application, and reflective evaluation — offers a transferable model for comparable engineering education contexts.

Keywords: Engineering literacy; Digital circuit design; Pedagogical innovation; Blended learning; Engineering education; Higher education

1 INTRODUCTION

The rapid advancement of information technology and artificial intelligence has intensified demands on engineering talent cultivation. China's New Engineering Education (XinGongKe) strategy emphasizes developing engineers with practical competence and innovative capacity aligned with industrial needs [1]. Within this framework, the "Digital Circuit and Logic Design" course serves as a foundational bridge in the electronic information curriculum, connecting fundamental theory with system-level engineering practice. However, effectively integrating engineering ability cultivation into such foundational courses remains a shared challenge across higher engineering education institutions.

Recent reform initiatives offer instructive precedents. Huazhong University of Science and Technology consolidated digital electronics and digital logic courses with a virtual experiment platform to promote theory-experiment integration [2]. The University of Electronic Science and Technology of China developed a Verilog/FPGA-centered practical teaching system [3]. Xidian University introduced domestic EDA tools through FPGA industry collaboration [4]. These initiatives advanced curriculum and technological dimensions of course reform, yet none systematically addressed the deep-rooted pedagogical imbalances — particularly the divide between analytical proficiency and design competence, and between component knowledge and system-level integration.

This paper presents a comprehensive pedagogical reform undertaken at Xi'an University of Posts and Telecommunications. Drawing upon over thirty years of course development, the teaching team conducted systematic diagnosis of instructional challenges informed by engineering education professional certification requirements, learning-condition surveys, and enterprise feedback. The resultant Up-IDEA teaching method, operationalized through a four-dimensional implementation framework, constitutes the methodological contribution of this study. The paper details the pedagogical rationale, architecture, implementation process, and empirical outcomes, offering a transferable reference for foundational engineering course reform.

2 LITERATURE REVIEW AND THEORETICAL FRAMEWORK

Engineering literacy encompasses the knowledge, skills, attitudes, and values that enable graduates to function effectively in engineering practice. The CDIO (Conceive, Design, Implement, Operate) framework has been widely adopted to structure engineering education around product lifecycle stages [5]. Similarly, active learning research consistently

demonstrates that student-centered, inquiry-based approaches improve performance in science, engineering, and mathematics [6]. Blended learning models, combining online and face-to-face instruction, have further expanded opportunities for flexible, personalized engineering education [7].

Within digital circuit education, reform efforts have focused on three primary directions: curriculum content reorganization [2, 8], practical teaching platform development [3-4], and assessment innovation [9-10]. However, many reforms remain siloed — addressing content or technology without systematically transforming pedagogical relationships. The gap between analytical proficiency and design competence, and between component knowledge and systems thinking, persists across many foundational engineering courses.

The present study draws upon three theoretical pillars. First, constructivist learning theory posits that learners actively construct knowledge through experience and social interaction, providing the rationale for problem-driven and inquiry-based instructional design. Second, Bloom's taxonomy of educational objectives informs the multi-level assessment design, ensuring alignment between learning activities and cognitive development levels [11]. Third, Felder and Brent's work on student differences guides the differentiated instruction dimension, recognizing that heterogeneous academic backgrounds require varied instructional pathways [12].

Building on these foundations, this study addresses two research questions: (1) Can a structured five-stage pedagogical cycle effectively cultivate engineering literacy in a foundational digital circuit course? (2) What dimensions of student learning show the most significant improvement following implementation?

3 METHOD

This study employed a design-based research approach, combining iterative pedagogical design with programmatic evaluation. The reform was implemented over three academic years in the “Digital Circuit and Logic Design” course at Xi'an University of Posts and Telecommunications.

3.1 Research Context and Participants

The course serves more than 2,000 students annually across 13 electronic information majors, representing approximately 60% of the university's engineering enrollment and supporting 10 first-class major programs. Course delivery accommodates program-specific requirements through 64- or 48-hour structures. The study population included students enrolled during the three-year reform implementation period. Pre-reform cohort data from the two years prior to implementation served as a historical comparison baseline.

3.2 The Four-Dimensional Implementation Framework

The reform was operationalized through four interdependent dimensions — content, resources, pedagogy, and assessment — collectively forming a coherent implementation architecture shown as Table 1. The Up-IDEA pedagogical cycle constitutes the core of this framework.

Table 1 The Four-Strengths-Four-Weaknesses to Four-Integrations to Four-Competences Reform Framework

Teaching Challenges (Four Strengths & Four Weaknesses)	Solutions (Four Integrations)	Learning Outcomes (Four Competences & Four Abilities)
Strong in Universality	Universal Instruction +	Knowledge Reconstruction
Weak in Differentiation	Personalized Cultivation	+ Innovative Thinking
Strong in Hardware	Engineering Design +	Technical Description
Weak in Software	Scientific Thinking	+ Academic Expression
Strong in Components	Online-Offline +	Knowledge Synthesis
Weak in Systems	Flipped Classroom	+ System Design
Strong in Analysis	Cutting-Edge Tech +	Engineering Design
Weak in Design	Research & Engineering Cases	+ Optimization

3.2.1 Content enhancement

Course content was upgraded to reflect the hardware “softwareization” trend: strengthening programmable device analysis and design, emphasizing hardware description language application, and incorporating cross-disciplinary engineering cases. An engineering case library was co-designed with industrial partners, embedding scientific thinking and engineering ethics throughout instruction. Research outcomes were transformed into teaching materials — for instance, a CRC check code generation circuit from the team's communication research became a teaching case for the shift register unit. Award-winning competition designs were systematically integrated into course content to achieve course-competition synergy.

3.2.2 Resource integration

The course, situated within the “Electronic Circuits and Systems Foundation” cluster, draws upon a comprehensive multi-format resource ecosystem: a published textbook (“Digital System and Logic Design”), bilingual courseware, and complete Chinese-English resources deployed across Chinese University MOOC, Zhihuishu, and Xuetang Online platforms. These resources support blended learning and flipped classrooms across different majors, supplemented by comprehensive problem sets for formative self-assessment.

3.2.3 The Up-IDEA pedagogical cycle

The Up-IDEA method constitutes the methodological core of the framework, shown as Figure 1, encoding a five-stage pedagogical cycle that forms a closed loop of teaching, learning, practice, and reflection:

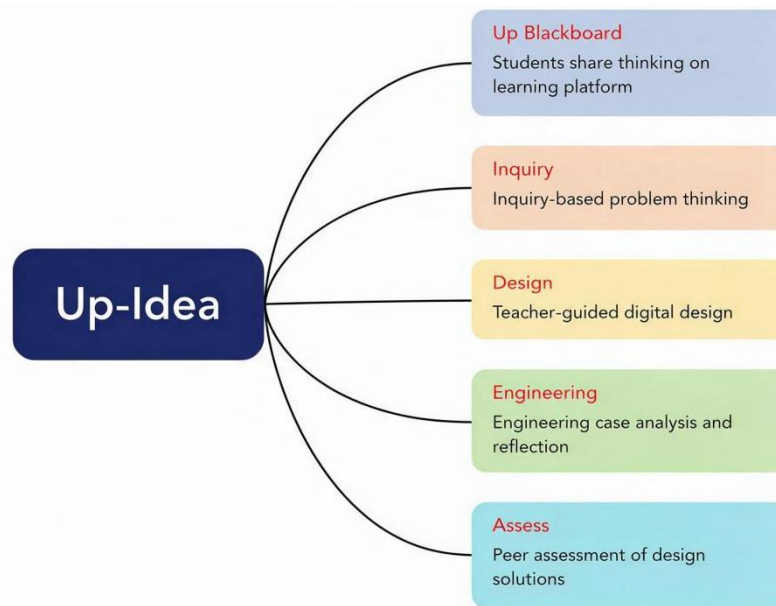


Figure 1 Up-IDEA Pedagogical Cycle

Stage 1 — Up: Pre-class Design Submission. Teachers publish carefully designed problems on the online learning platform before class. Students submit preliminary design proposals, which stimulates engagement with engineering problems while generating diagnostic learning-condition data for targeted instructional planning.

Stage 2 — Inquiry: Problem-Driven Engagement. Class sessions open with collaborative examination of student submissions and peer discussion to address common conceptual difficulties, followed by guided inquiry introducing new content. Real-time feedback instruments — including Rain Classroom and the Xuexitong platform — enable dynamic adjustment of instructional strategy based on continuous assessment of comprehension.

Stage 3 — Design: Software-Based Hardware Design. Pedagogical scaffolding guides students to employ Verilog HDL for hardware circuit description in units such as state machine design and shift register circuits, internalizing the software-based design methodology central to contemporary digital systems engineering.

Stage 4 — Engineering: Case-Based Application. Engineering design cases aligned with international standards are incorporated, drawing on cooperative education resources. Engineering ethics are systematically integrated into instruction. Structured post-class reflection requirements enable students to consolidate knowledge relationships and cultivate critical thinking.

Stage 5 — Assess: Reflective Evaluation. Grounded in Bloom's taxonomy [11], evaluation activities guide students to critically appraise design solutions, consolidating cognitive development. Multi-dimensional assessment mechanisms — peer evaluation, self-assessment, and instructor evaluation — stimulate deep learning motivation and reinforce metacognitive awareness.

3.2.4 Multi-dimensional assessment

Course delivery allocates total class hours at a 1:5:2 ratio across online, on-site, and engineering case instruction. The assessment system synthesizes four complementary perspectives: process and outcome, quantitative and qualitative measures, individual and collaborative performance, and ability and literacy dimensions.

The final grade comprises regular assessment (50%) and a comprehensive final examination (50%). Regular assessment evaluates blended learning engagement — online activities (video learning, preview, discussion, reflection journals, extension tasks, peer evaluation) and offline activities (classroom interaction, presentations, group discussion, periodic assessments) — as well as design implementation, requiring students to complete Multisim simulation projects collaboratively in groups of two to four with oral defense. Weekly reflection journals, deliberately designed without standard answers, encourage critical thinking and combine quantitative metrics with qualitative evaluation.

3.3 Data Collection and Analysis

Programmatic evaluation triangulated three data sources to assess reform outcomes. First, learning platform analytics captured objective engagement metrics including attendance, homework completion, pre-class problem resolution rates, and participation in online discussions. Second, end-of-course questionnaire surveys collected student self-perceptions of learning outcomes and satisfaction. Third, institutional teaching assessment data and competition award records provided independent indicators of engineering practice capability.

Descriptive statistics were computed for all quantitative measures. Comparative analysis with pre-reform historical data was conducted where comparable metrics were available. Qualitative data from student reflections and peer evaluations were analyzed thematically to supplement quantitative findings. The triangulation of multiple data sources strengthened the validity of conclusions by providing converging evidence of improvement.

4 RESULTS

Implementation of the Up-IDEA framework yielded measurable improvements across three principal dimensions: student engagement, autonomous learning, and engineering practice capability. Findings are presented below, organized by dimension.

4.1 Student Engagement

The reform significantly elevated student participation metrics. Class attendance reached 98% across the implementation period, compared with 92% in the pre-reform baseline. Classroom discussion, group work, and Q&A participation each approximated 90%, compared with approximately 65–70% prior to the reform. Homework completion reached 100%, reflecting the efficacy of participation-embedded instructional design. These improvements suggest that the pre-class diagnostic mechanism and problem-driven classroom structure effectively sustain learner engagement throughout the course cycle.

4.2 Autonomous Learning

More than 80% of students independently resolved over 70% of pre-class learning problems, indicating meaningful development of learning initiative and independent problem-solving capability. Pre-reform data showed approximately 40–50% of students completing pre-class preparatory work, with lower rates of independent problem resolution. The shift toward self-directed learning is consistent with the framework's emphasis on inquiry-based engagement and metacognitive evaluation.

Analysis of reflection journals revealed that students increasingly demonstrated higher-order cognitive skills over the course semester. Early-semester reflections primarily described procedural steps, while later reflections more frequently addressed design trade-offs, alternative solutions, and systemic relationships — patterns consistent with progression along Bloom's taxonomy from understanding toward evaluation and creation.

4.3 Engineering Practice Capability

The “Dingyang Cup” and “Yushi Cup” school-enterprise competition platforms, featuring enterprise expert review, facilitated application of classroom knowledge to authentic engineering challenges. Over three years, 342 students received national or provincial awards in electronic design and FPGA competitions, including national-level prizes in the Undergraduate Electronic Design Contest and the FPGA Innovation Design Competition. While this outcome reflects multiple contributing factors — including institutional resources and faculty research strength — the magnitude and consistency of awards across the implementation period suggest positive alignment between the pedagogical framework and engineering practice outcomes.

4.4 Student Perceptions

End-of-course surveys indicated high levels of student satisfaction, with over 90% of respondents agreeing or strongly agreeing that the course improved their engineering design ability. Students particularly valued the pre-class problem engagement, the Verilog-based design experience, and the connection between course content and real-world engineering applications. Common themes in open-ended responses included appreciation for the practical orientation of the course and increased confidence in approaching complex design problems.

5 DISCUSSION

The empirical findings provide converging evidence that a structured five-stage pedagogical cycle can effectively foster engineering literacy in a foundational engineering course. The substantial gains in participation metrics — 98% attendance and 100% homework completion — suggest that the closed-loop pedagogical structure effectively sustains learner engagement. The pre-class diagnostic mechanism appears particularly consequential: by generating learning-condition data before instruction, teachers can calibrate classroom delivery to actual student needs, potentially explaining the high autonomous learning rate.

5.1 Theoretical Implications

The results are consistent with constructivist learning theory, which posits that active engagement with authentic problems enhances knowledge retention and transfer. The improvement in engineering practice outcomes aligns with CDIO principles, which emphasize integrating product lifecycle perspectives into engineering education [5]. The finding that

participation increases were accompanied by improved problem-solving ability supports active learning research showing that engagement alone is insufficient — structured cognitive scaffolding is necessary to produce learning gains [6]. The five-stage cycle contributes to the literature by specifying how blended learning can be operationalized in engineering foundational courses. While previous research has documented the benefits of flipped classrooms and online learning [7, 13], the Up-IDEA framework offers a more granular model that integrates pre-class preparation, classroom inquiry, design practice, engineering application, and reflective assessment into a coherent pedagogical architecture.

5.2 Practical Implications

The framework's modular design — with content, resources, pedagogy, and assessment as separable but interdependent dimensions — suggests potential for adaptation to other engineering foundational courses. The Up-IDEA cycle itself is domain-agnostic in structure, though the specific content, cases, and tools would require contextualization for different disciplinary contexts. The multi-dimensional assessment approach also offers a model for programs seeking to evaluate engineering literacy development beyond traditional examination metrics.

5.3 Limitations

Several limitations of this study should be acknowledged. First, the evaluation employs a quasi-experimental design without randomized control groups; while pre-reform comparison data and triangulated evidence provide support for the reform's efficacy, causal attribution to specific method components cannot be firmly established. Second, the differential effectiveness of individual framework dimensions was not independently assessed, limiting component-level understanding of what drives outcomes. Third, the study was conducted at a single institution, which may limit generalizability to other institutional contexts with different student populations, resource levels, or disciplinary emphases. Fourth, the engineering practice outcomes — while notable — reflect multiple contributing factors beyond pedagogy, including institutional investment in competition platforms, faculty research involvement, and student self-selection into competitive activities. Finally, the evaluation focuses on course-level outcomes; longer-term impacts on subsequent course performance, internship quality, or graduate employment trajectories were not assessed.

6 CONCLUSION

This study presents the Up-IDEA pedagogical framework for cultivating engineering literacy in foundational engineering courses, implemented in a Digital Circuit and Logic Design course serving more than 2,000 students across 13 majors. The five-stage cycle — Up (pre-class design submission), Inquiry (problem-driven engagement), Design (software-based hardware practice), Engineering (case-based application), and Assess (reflective evaluation) — establishes a closed-loop pedagogical architecture in which preparation, instruction, practice, application, and reflection form a unified learning cycle.

Triangulated evaluation evidence indicates significant improvements in student engagement, autonomous learning capacity, and engineering practice outcomes. The four-dimensional implementation framework — integrating content enhancement, resource integration, Up-IDEA pedagogy, and multi-dimensional assessment — provides a coherent model for engineering literacy cultivation that is potentially transferable to other foundational engineering courses.

Future research directions include: controlled comparative studies with matched cohorts to strengthen causal inference; longitudinal tracking of learning outcomes across subsequent courses and into professional practice; component-level analysis to isolate the contribution of each pedagogical stage; and exploration of AI-adaptive learning technologies to further personalize learning pathways within the framework.

COMPETING INTERESTS

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

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