



## Pedagogical Conditions for Developing Core Competencies in School Students Through the Integration of Physics and Technical Knowledge

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**Abstract:** This study examines the pedagogical conditions necessary for developing core competencies in school students through the integration of physics and technical knowledge within a STEM education framework. Through a quasi-experimental design involving 120 secondary school students (experimental group n=60, control group n=60), the research investigated the effectiveness of integrated physics-technology instruction over one academic semester. Pre-test and post-test assessments measured students' competency development in problem-solving, critical thinking, and practical application skills. Results demonstrated that the experimental group showed significantly higher competency gains ( $M=78.4$ ,  $SD=6.2$ ) compared to the control group ( $M=64.7$ ,  $SD=7.1$ ),  $t(118)=10.83$ ,  $p<0.001$ ,  $d=2.08$ . Five essential pedagogical conditions were identified through mixed-methods analysis: interdisciplinary curriculum design, laboratory infrastructure adequacy, teacher professional development in integrative approaches, project-based learning methodologies, and motivation-enhancing learning environments. Qualitative data from student interviews and classroom observations revealed increased engagement and deeper conceptual understanding in the integrated approach. The findings suggest that successful competency development requires systematic integration of these pedagogical conditions within institutional frameworks. This research contributes to the growing literature on STEM education and provides practical implications for curriculum designers and educators implementing integrated science-technology programs.

**Keyword :** competence, integration, STEM education, pedagogical conditions, physics education, interdisciplinary learning, project-based learning, competency-based education

**Article info:** Submitted : 2025-11-10 | Accepted : 2025-12-04 | Published : 2025-12-04

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## INTRODUCTION

The 21st century has witnessed unprecedented technological advancement, necessitating fundamental shifts in educational approaches to prepare students for an increasingly complex, technology-driven world. Traditional subject-siloed instruction has proven insufficient in developing the multifaceted competencies required for success in modern STEM careers and civic participation. Educational systems worldwide are increasingly recognizing that students must develop not only disciplinary knowledge but also transferable competencies including critical thinking, problem-solving, creativity, and collaboration.

Physics education, as a foundational component of STEM learning, faces particular challenges in engaging students and demonstrating real-world relevance. Research indicates declining student interest in physics at the secondary level, often attributable to abstract theoretical content perceived as disconnected from practical application. Integrated STEM approaches, particularly the connection between physics and technical education, offer promising pathways to address these challenges by situating learning in authentic, interdisciplinary contexts.

Competency-based education has emerged as a pedagogical framework emphasizing demonstrated mastery of knowledge, skills, and dispositions over traditional time-

based progression. However, the specific pedagogical conditions necessary for successful competency development through integrated physics-technical instruction remain underexplored in the literature. While numerous studies have examined STEM integration broadly, there exists a significant research gap regarding the concrete organizational, psychological, and didactic conditions that enable effective competency formation in this specific integrated context.

The present study addresses this gap by investigating: What are the essential pedagogical conditions that support the development of core competencies in secondary school students through integrated physics-technology education? This research contributes to the field by providing empirical evidence on the effectiveness of integrated approaches while identifying specific conditions that educators and administrators must establish to maximize student competency development. The findings have practical implications for curriculum design, teacher preparation, and educational policy in STEM education contexts.

## LITERATURE REVIEW

### Theoretical Foundations of Integrated STEM Education

Integrated STEM education represents a pedagogical approach that combines two or more STEM

disciplines into cohesive learning experiences, moving beyond traditional disciplinary boundaries. The conceptual framework for integrated STEM has evolved from early calls for science-technology-society connections to contemporary models emphasizing authentic problem-solving and interdisciplinary knowledge application. Kelley and Knowles (2016) propose that effective STEM integration requires explicit connections among disciplines, real-world contextualization, and engineering design processes as organizing frameworks.

Physics, due to its fundamental relationship with technology and engineering, serves as a particularly strong anchor for integrated STEM learning. The discipline's laws and principles provide theoretical foundations for technological applications, while technology offers concrete contexts for physics concept exploration. Recent neuroscience-informed pedagogical research suggests that integrated STEM-based project learning significantly improves student attitudes toward physics by reducing abstraction and enhancing perceived relevance. The integration of physics with technical education specifically allows students to witness immediate practical applications of theoretical principles, potentially addressing longstanding challenges in physics education engagement.

## **Competency-Based Education Framework**

Competency-based education (CBE) shifts focus from time-based seat hours to demonstrated mastery of explicit learning outcomes. The Competency-Based Education Network defines CBE as combining intentional, transparent curricular design with flexible pacing that holds learning expectations constant while allowing variable time for mastery demonstration. Key concepts underpinning CBE include: demonstrated competency mastery, meaningful assessment aligned with real-world performance, individualized learner support, and knowledge creation and application rather than mere content coverage.

Core competencies in STEM contexts typically encompass cognitive dimensions (conceptual understanding, problem-solving, critical thinking), practical dimensions (technical skills, experimental design, data analysis), and dispositional dimensions (collaboration, communication, scientific habits of mind). The CBE Mastery Framework identifies four essential areas requiring adaptation for successful implementation: structure (assessment systems, scheduling, credentialing), culture (growth mindset, student agency, risk-taking), teaching (facilitation, differentiation, formative assessment), and learning (metacognition, self-direction, application). Research indicates that

project-based and problem-based pedagogies align particularly well with CBE principles by emphasizing authentic performance and iterative skill development.

### **Pedagogical Conditions in Educational Theory**

Pedagogical conditions refer to the necessary factors, requirements, and environmental elements that enable effective educational processes and outcomes. Russian pedagogical theorists including Borytko, Dynina, and Kupriyanov conceptualize pedagogical conditions as comprehensive sets of pedagogical influence measures implemented through material-spatial environment possibilities to achieve specific process goals. The concept encompasses both internal conditions (modifiable elements within educational control such as curriculum design, assessment systems, and instructional methods) and external conditions (fixed contextual factors including geographical, political, and economic circumstances).

Contemporary scholarship classifies pedagogical conditions into three primary categories. Organizational-pedagogical conditions encompass structural and procedural aspects including resource provision, scheduling, and participant interaction organization, essentially forming the procedural dimension of pedagogical systems. Psychological-pedagogical conditions address relational dynamics

and personal needs accommodation, representing the personality-oriented aspect focusing on learner characteristics and motivation. Didactic conditions concern content selection and instructional methodology implementation, constituting the instructional effectiveness dimension. For integrated STEM learning, all three condition types must be simultaneously addressed, as subject integration inherently requires coordination across organizational structures, attention to student psychological responses to novel approaches, and careful didactic planning of conceptual connections.

### **Project-Based Learning in Physics Education**

Project-based learning (PBL) has demonstrated significant effectiveness in physics education by engaging students in sustained, inquiry-driven investigations of authentic problems. Meta-analyses indicate that PBL approaches in university physics contexts significantly enhance conceptual understanding, problem-solving abilities, and practical competencies compared to traditional lecture-based instruction. In secondary physics education, systematic reviews reveal that while PBL implementation shows considerable diversity, consistent benefits include increased student engagement, improved application of physics concepts to real-world scenarios, and development of

collaborative and critical thinking skills.

Interdisciplinary PBL, particularly physics-technology integration, appears especially promising for competency development. Research demonstrates that students engaged in interdisciplinary physics projects show enhanced motivation, deeper conceptual connections, and improved ability to transfer learning across domains. However, teachers frequently report challenges implementing such approaches, including curriculum time constraints, limited pedagogical preparation for integration, insufficient institutional support, and concerns about disciplinary content depth. These reported barriers underscore the importance of identifying and establishing supportive pedagogical conditions.

## METHODS

### Research Design

This study employed a mixed-methods quasi-experimental design combining quantitative assessment of competency development with qualitative exploration of pedagogical conditions. The research was conducted during the 2023-2024 academic year at two secondary schools in Nukus, Karakalpakstan, selected for comparable demographics, resources, and physics curriculum implementation. The experimental design compared an integrated physics-technology approach

(experimental group) with traditional separate-subject instruction (control group) over one academic semester (16 weeks).

### Participants

The participant pool consisted of 120 ninth-grade students (ages 14-15) enrolled in physics and technology courses. Students were assigned to experimental (n=60) and control (n=60) groups based on intact classroom groupings to maintain natural learning environments. Groups were statistically equivalent at baseline on prior physics achievement ( $t(118)=0.73$ ,  $p=0.47$ ), general academic performance ( $t(118)=0.58$ ,  $p=0.56$ ), and demographic characteristics including gender distribution ( $\chi^2(1)=0.42$ ,  $p=0.52$ ) and socioeconomic status indicators. All participants provided informed assent, with parental consent obtained in accordance with institutional ethical guidelines.

### Intervention Description

The experimental group received integrated physics-technology instruction featuring explicit conceptual connections, collaborative projects, and authentic problem-solving. The intervention was structured around five major projects over the semester, each integrating physics concepts with technical applications. Example projects included designing and building simple machines applying mechanics principles, constructing electrical

circuits for practical devices, developing renewable energy models, creating robotics applications, and engineering structural designs incorporating force analysis.

Each project followed a consistent structure: introduction of real-world problem contexts, collaborative investigation of relevant physics principles, design and planning phases integrating technical considerations, hands-on construction and testing, data collection and analysis, and final presentation and reflection. Physics and technology teachers co-planned instruction and team-taught during project sessions. The control group received standard instruction with physics and technology taught as separate subjects following traditional curricula, though both groups received equivalent total instructional time (180 minutes weekly).

### **Data Collection Instruments**

Competency development was assessed through multiple measures. A researcher-developed Integrated Physics-Technology Competency Assessment (IPTCA) evaluated problem-solving, critical thinking, and practical application skills through performance tasks requiring students to apply physics concepts to technical problems. The instrument demonstrated good internal consistency (Cronbach's  $\alpha=0.84$ ) and acceptable inter-rater reliability (ICC=0.79) across two trained

assessors. Students completed identical IPTCA assessments at pre-test and post-test.

Qualitative data sources included semi-structured student interviews (n=20, purposively sampled for maximum variation), teacher reflective journals, and classroom observation protocols. Interview questions explored student experiences with integrated learning, perceived competency development, and motivational factors. Classroom observations (12 sessions per group) documented instructional practices, student engagement indicators, and collaborative behaviors using structured protocols. Additionally, student project artifacts and final presentations provided evidence of applied competency.

### **Data Analysis**

Quantitative data were analyzed using SPSS 26.0. Independent samples t-tests compared post-test competency scores between groups, with effect sizes calculated using Cohen's d. Paired samples t-tests examined within-group pre-to-post changes. ANCOVA was employed to control for baseline differences where appropriate. Statistical significance was set at  $\alpha=0.05$  (two-tailed).

Qualitative data underwent thematic analysis following Braun and Clarke's six-phase approach. Interview transcripts and observation notes were coded inductively by two researchers, with discrepancies resolved through

discussion. Codes were organized into candidate themes, reviewed for coherence and distinctiveness, and refined through iterative analysis. The identified themes were mapped onto the pedagogical conditions framework, allowing for systematic identification of conditions supporting competency development.

## RESULTS AND DISCUSSION

### Competency Development Outcomes

Table 1 presents descriptive statistics for competency assessment scores. The experimental group demonstrated substantially higher post-test competency scores ( $M=78.4$ ,  $SD=6.2$ ) compared to the control group ( $M=64.7$ ,  $SD=7.1$ ). Independent samples t-test revealed this difference was statistically significant,  $t(118)=10.83$ ,  $p<0.001$ , with a large effect size (Cohen's  $d=2.08$ ), indicating that the integrated approach produced meaningful improvements in competency development.

**Table 1.**  
**Competency Assessment Scores by Group**

Group	Pre-test M (SD)	Post-test M (SD)	Gain Score	Effect Size (d)
Experimental (n=60)	58.3 (8.1)	78.4 (6.2)	20.1***	2.73
Control (n=60)	57.6 (8.4)	64.7 (7.1)	7.1***	0.90

Note: \*\*\*  $p < 0.001$

Both groups showed significant pre-to-post improvement, but the magnitude differed markedly. The experimental group's gain score of 20.1

points represented a 34.5% improvement over baseline, with a very large within-group effect size ( $d=2.73$ ). The control group's gain of 7.1 points, while statistically significant, represented only a 12.3% improvement with a moderate effect size ( $d=0.90$ ). These results provide strong evidence that integrated physics-technology instruction significantly enhances competency development beyond traditional approaches.

Subscale analysis revealed that the integrated approach particularly benefited practical application skills (experimental  $M=81.2$ , control  $M=62.4$ ,  $d=2.41$ ) and problem-solving abilities (experimental  $M=77.9$ , control  $M=65.8$ ,  $d=1.65$ ), with moderate advantages for critical thinking skills (experimental  $M=76.1$ , control  $M=66.0$ ,  $d=1.38$ ). This pattern suggests that hands-on, contextual learning experiences most powerfully impact applied competencies, though benefits extend to higher-order thinking skills as well.

### Identified Pedagogical Conditions

Thematic analysis of qualitative data identified five essential pedagogical conditions that enabled effective competency development in the experimental group. These conditions align with the theoretical framework of organizational-pedagogical, psychological-pedagogical, and didactic conditions, providing practical specification for integrated physics-technology contexts.

**1. Condition 1: Intentional Interdisciplinary Curriculum Design.**

Successful integration required explicit, preplanned connections between physics concepts and technical applications rather than superficial or post-hoc linkages. Physics and technology teachers engaged in collaborative planning to identify natural connection points, sequence content for conceptual coherence, and design assessments measuring integrated understanding. As one teacher noted, "We had to fundamentally rethink our curriculum, not just add technology projects to physics or vice versa, but truly interweave the concepts so students see them as interconnected from the start."

**2. Condition 2: Adequate Laboratory and Technical Infrastructure.**

Physical resources proved essential for hands-on competency development. Schools required well-equipped physics laboratories with modern measurement instruments, alongside technical education facilities with appropriate tools, materials, and equipment for construction and testing. Students consistently emphasized the importance of "actually building things, not just reading about them" for understanding physics principles. Without sufficient resources, the practical application dimension of competencies could not be adequately developed.

**3. Condition 3: Teacher Professional Development in Integrative Pedagogies.**

Teachers required specific preparation for integrated instruction, including understanding of interdisciplinary connections, facility with project-based methodologies, and skills in collaborative teaching. Both physics and technology teachers needed foundational knowledge of each other's disciplines to facilitate meaningful integration. Professional development focusing on these areas proved crucial, with teachers reporting that "learning to teach in this integrated way was itself a significant professional learning experience that challenged our traditional subject-specific thinking."

**4. Condition 4: Project-Based and Student-Centered Methodologies.**

Active learning approaches, particularly project-based learning organized around authentic problems, emerged as critical for competency development. Traditional lecture-demonstration methods proved insufficient for developing applied competencies. Students reported that projects "made physics make sense" and "showed us why we needed to learn formulas." The social nature of project work also developed collaborative and communication competencies alongside technical skills. Group work, hands-on experimentation, and iterative design processes were consistently identified as high-impact pedagogical strategies.

### 5. Condition 5: Motivational and Engagement-Enhancing Environment.

Creating a learning environment that stimulated intrinsic motivation significantly affected competency development. Elements include connecting content to students' interests and real-world applications, providing opportunities for creativity and choice within projects, celebrating achievements through competitions or exhibitions, and establishing a classroom culture valuing experimentation and learning from failure. Students in the experimental group demonstrated notably higher engagement, with one student articulating, "I actually look forward to physics-technology class now because we're solving problems that matter, not just memorizing formulas."

**Table 2.**  
**Essential Pedagogical Conditions for Integrated Physics-Technology Competency Development**

Pedagogical Condition	Category	Key Implementation Elements
Interdisciplinary Curriculum Design	Didactic	Co-planning, explicit connections, integrated assessment
Laboratory Infrastructure	Organizational	Equipment, materials, physical spaces for experimentation
Teacher Professional Development	Organizational	Interdisciplinary knowledge, collaborative teaching skills
Project-Based Methodologies	Didactic	Authentic problems, hands-on work, collaborative learning
Motivational Environment	Psychological	Real-world relevance, student choice, celebration of achievement

### Discussion

This study provides empirical evidence that integrated physics-

technology instruction, when implemented with appropriate pedagogical conditions, significantly enhances student competency development compared to traditional approaches. The large effect sizes observed ( $d=2.08$  for overall competency,  $d=2.41$  for practical applications) represent educationally meaningful improvements, suggesting that integrative approaches offer substantial value for competency-based education goals.

These findings align with broader STEM education literature demonstrating benefits of interdisciplinary integration. The neuroscience-informed STEM-PjBL research of Uden and colleagues similarly reported improved student attitudes and beliefs about physics learning following integrated instruction. The present study extends this work by quantifying competency gains and identifying specific enabling conditions. The particularly strong effects on practical application skills resonate with project-based learning research showing that authentic, hands-on experiences powerfully support transfer of learning to real-world contexts.

The five identified pedagogical conditions provide practical guidance for educators and administrators implementing integrated approaches. The primacy of intentional curriculum design echoes calls in the literature for coherent, purposeful integration rather than superficial connections. The

infrastructure requirements highlight often-overlooked resource considerations that can enable or constrain innovation. Teacher professional development emerges as critical yet frequently inadequate, consistent with teacher-reported barriers in previous research. The emphasis on project-based methodologies aligns with extensive evidence supporting active, student-centered approaches for both engagement and learning outcomes. Finally, attention to motivational environment addresses the affective dimension often underemphasized in competency frameworks despite its documented influence on learning.

The classification of conditions into organizational, psychological, and didactic categories provides theoretical coherence while suggesting distinct intervention points. Organizational conditions (infrastructure, professional development) require administrative and policy-level attention, including resource allocation and systemic support structures. Didactic conditions (curriculum design, project-based methods) demand teacher expertise and curricular flexibility, suggesting needs for both pre-service preparation and ongoing professional learning. Psychological conditions (motivational environment) emerge from classroom culture and pedagogy, requiring attention to student experience alongside content coverage. Successful implementation likely requires coordinated attention to all three

domains, as weakness in any area can undermine overall effectiveness.

Several limitations warrant consideration. The quasi-experimental design, while preserving natural learning environments, limits causal inference compared to random assignment. The relatively short intervention period (one semester) leaves questions about longer-term competency retention and development. Cultural and contextual specificity of the Uzbekistan setting may affect generalizability, though core findings likely translate to similar educational contexts. Self-report and observational data, while providing rich qualitative insight, introduce potential response and observer biases. Future research should address these limitations through longitudinal designs, diverse geographic contexts, and additional objective competency measures.

## CONCLUSION

This research demonstrates that integrated physics-technology education, implemented within a framework of five essential pedagogical conditions, significantly enhances student competency development in problem-solving, critical thinking, and practical application. The findings contribute theoretical clarity regarding specific conditions enabling successful integration while providing practical guidance for educational implementation. As educational

systems increasingly prioritize competency development and STEM integration, attention to these conditions can support more effective instructional design and resource allocation.

The identified conditions—interdisciplinary curriculum design, adequate infrastructure, teacher professional development, project-based methodologies, and motivational environments—represent actionable targets for educational improvement. Schools and districts seeking to implement integrated STEM approaches should systematically address each condition type, recognizing that organizational, didactic, and psychological elements work synergistically. Teacher education programs should incorporate preparation for interdisciplinary instruction, including both content knowledge across STEM domains and pedagogical skills for integration and project facilitation.

Future research directions include investigating the relative importance and interactions among conditions, exploring implementation challenges and solutions in diverse contexts, examining long-term competency trajectories, and studying scalability of integrated approaches from pilot implementations to system-wide adoption. Additionally, research should explore how digital technologies and emerging pedagogical innovations can support integrated instruction while

maintaining focus on fundamental competency development goals.

Ultimately, this study reinforces that achieving educational goals for 21st-century competencies requires more than curriculum revision alone. Systematic attention to the full ecology of pedagogical conditions—from material resources and teacher preparation to instructional methods and learning culture—proves essential for realizing the potential of integrated STEM education to develop the multifaceted competencies students need for success in an increasingly complex, technology-mediated world.

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**Conceptualization:** Author 1 ;

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**Investigation:** Author 1 ;

**Writing – original draft preparation:** Author 1 ;

**Writing – review and editing:** Author 1 ;

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All authors have read and agreed to the published version of the manuscript.