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ENHANCING SPATIAL COMPETENCIES THROUGH DI-DACTIC STRATEGIES IN ENGINEERING DYNAMICS: A CASE STUDY IN LIMA, PERU

Hans Aaron Vilchez Chumpitaz [1] , Herbert Robles Mori[2]

[1] Lima, La Molina, Paseo del Prado Street 110 - Universidad San Ignacio De Loyola, Lima – Peru Lima, PERU

e-mail: hans.vilchez@epg.usil.pe

[2] Lima, La Molina, La Fontana Avenue 750 - Universidad San Ignacio De Loyola, Lima – Peru Lima, PERU

e-mail: herbert.robles@epg.usil.pe

Abstract

Spatial skills are essential in engineering but are often neglected in curricula. The lack of training in geometry or technical drawing makes it difficult for students to understand three-dimensional concepts, affecting their performance in courses such as Dynamics. This research employed a mixed-methods approach with a quasi-experimental design and pre- and post-intervention measurements. The results show that spatial reasoning in engineering improves through technology-assisted instruction combining drawing, modeling, and visualization, strengthening comprehension and engagement. The study supports experiential learning and promotes greater emphasis on spatial training in engineering education.

Keywords: Spatial reasoning, engineering education, technology-assisted instruction, experiential learning, visualization.

1. Introduction

In the context of engineering education, the ability to mentally manipulate three-dimensional objects and understand spatial relationships is not simply an added skill but a core competency. Spatial reasoning allows students to visualize abstract physical phenomena, interpret vector movements, and translate real-world mechanics into schematic representations. These abilities, commonly referred to as spatial competencies, play a critical role in understanding and solving problems in courses such as Dynamics, where students must model forces acting on structures in motion. Despite their importance, spatial competencies are often underrepresented in curricula, especially in foundational engineering courses, which tend to emphasize mathematical rigor while overlooking cognitive skills essential to spatial interpretation [1].

A significant number of students enter higher education without having developed adequate spatial skills during their earlier schooling. Traditional subjects that supported such development, like technical drawing, geometry, and manual drafting, have either diminished in academic weight or disappeared altogether from school programs. In their place, more abstract and standardized content has taken root, creating a vacuum in the kind of manipulative, visual learning that spatial reasoning demands. Consequently, students face increased difficulty in

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visualizing concepts that require three-dimensional interpretation, leading to poor performance in technical subjects like Dynamics, where success depends not only on solving equations but on mentally simulating spatial conditions [2,3].

This phenomenon is neither novel nor exclusive to one country. International studies have highlighted similar issues across diverse educational systems. In Spain, researchers observed that students with prior exposure to spatial manipulation through drawing or construction tasks achieved better results in physics and mechanics courses. In Saudi Arabia, Sheharyar and colleagues reported that limited experience with visual models among engineering students correlated with low achievement in interpreting three-dimensional force systems. In the United States, Sorby's long-term investigations have shown that early intervention with spatial training significantly improves performance in STEM programs, particularly for students who initially tested low on spatial assessments. South Korean researchers also found that interactive spatial tasks increase long-term retention of structural concepts and foster deeper learning [4–6]. These findings confirm that spatial abilities are teachable and that educational systems must actively in-corporate strategies to strengthen them from the early stages of technical training.

In Peru, these challenges are compounded by broader issues in talent development. According to the 2023 Global Talent Competitiveness Index, Peru ranks 34th out of 43 countries, reflecting serious deficiencies in educational infrastructure, talent retention, and technical training aligned with labor market demands. Although some progress has been made to attract new talent, the report identifies a persistent weakness in the development of specialized skills, particularly in STEM areas. This gap suggests a disconnect between what students learn in classrooms and what employers expect in professional environments [7]. In such a context, fostering spatial competencies is no longer optional but essential for ensuring academic success and employability in engineering fields.

One critical factor aggravating the spatial skill gap is the decreasing number of instructional hours dedicated to visual-spatial training. Courses such as technical drawing and graphical expression are often reduced or removed in favor of more digitally oriented subjects. While digital tools like computer-aided design (CAD) software provide students with precision and speed, they do not necessarily promote deep internalization of spatial concepts. In fact, over-reliance on automated processes may hinder the development of students' ability to mentally visualize complex structures. The shift toward digital platforms, although beneficial in many aspects, risks creating a generation of engineers who are proficient in software use but lack intuitive understanding of physical space and geometry [8,9].

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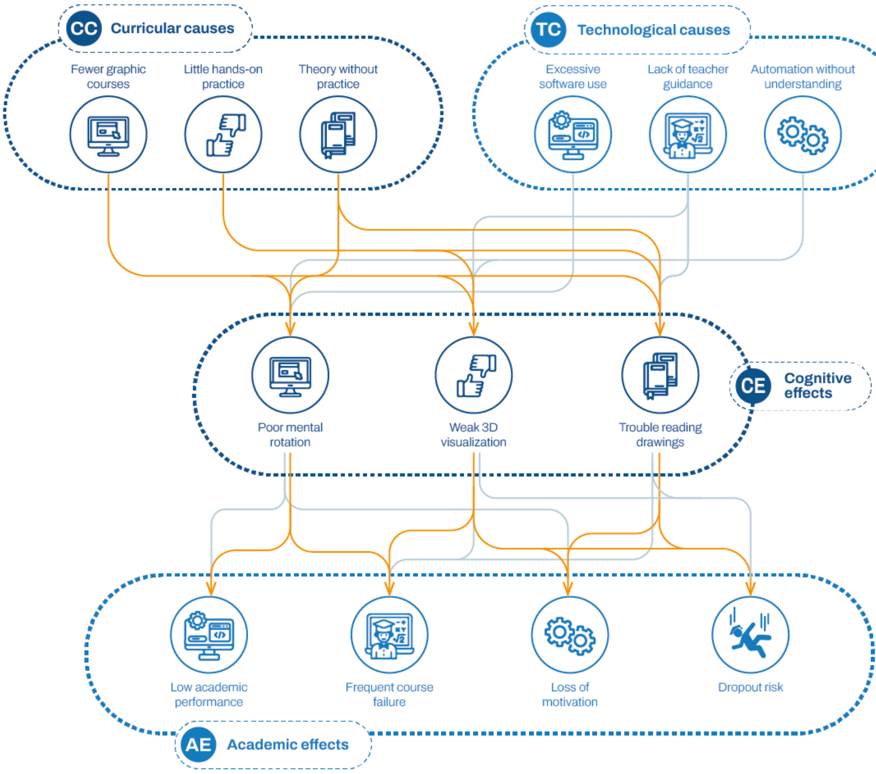

Figure 1. Causal model of the gap between technological automation and spatial skills in engineering students.

Figure 1 illustrates this divergence between digital and manual spatial processing. It shows how students' reliance on automated tools may streamline modeling tasks but re-duce the cognitive effort involved in imagining spatial transformations. Without sufficient training in visual thinking, students may produce technically correct outputs without fully grasping the underlying spatial logic.

In response to these concerns, educators and researchers have explored the integration of emerging technologies that reintroduce spatial reasoning through interactive and constructivist methods. Augmented Reality (AR), for instance, enables the projection of three-dimensional objects into real-world environments, offering learners a way to observe, manipulate, and understand spatial relationships in real time. Rather than passively observing diagrams, students become active participants who can explore different angles, dissect structures, and gain a more intuitive grasp of spatial configurations [10]. This approach aligns with cognitive theories that highlight the importance of embodied learning and multisensory engagement in conceptual development.

Isometric projection techniques have also proven valuable in reinforcing spatial awareness. These techniques allow learners to depict three-dimensional structures in two-dimensional formats without distorting proportions. They are widely used in architectural and mechanical design and are fundamental to developing accurate spatial perceptions. When students learn to interpret and construct isometric drawings, they simultaneously develop the ability to reason

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through spatial transformations, a skill crucial in fields like structural engineering, robotics, and manufacturing [11].

Additionally, the introduction of 3D printing technologies into classroom settings has brought about transformative learning opportunities. By converting digital models into physical objects, 3D printers allow students to bridge the gap between abstract design and tangible experience. Handling printed objects encourages learners to reflect on dimensions, tolerances, and geometrical relationships. They can rotate, measure, and inspect models in ways that virtual platforms cannot replicate. This process not only rein-forces their understanding but also fosters a mindset of prototyping and iterative design [12].

Table 1. Educational technologies for strengthening spatial competencies in engineering.

Tool/Strategy	Application in the Classroom
Augmented Reality	Visualization and manipulation of 3D models
Isometric Projections	Spatial drawing without distortion
3D Printing	Physical realization of digital models
Specialized Software	Simulation of complex technical systems

Table 1 summarizes the principal technological tools currently used to promote spatial competencies in engineering education, along with their educational functions and associated literature.

These tools work best not in isolation but as part of a blended learning approach. Re-search by Fang et al. has shown that combining digital tools with hands-on resources leads to deeper conceptual understanding. When students are allowed to switch between screens and real objects, seeing, touching, and modifying representations, they construct more robust mental models of spatial phenomena [14].

At the institutional level, these observations have motivated a shift in pedagogical design, especially in programs where spatial reasoning is a known learning bottleneck. The current study emerges from the recognition that the difficulties students face in mastering Dynamics are not rooted solely in the complexity of the subject but in the underdevelopment of foundational spatial skills. As such, the present work is not merely an instructional redesign, but a pedagogical intervention aimed at addressing the root causes of academic struggle in technical courses.

The strategies proposed in this study are based on the constructivist view that learning is an active process where knowledge is built through experience, manipulation, and reflection. Educational approaches rooted in constructivism encourage learners to test ideas, engage in trial and error, and reconstruct their understanding through interaction with both physical and digital tools. This theoretical perspective provides the basis for the instructional design model adopted in this research [15].

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Project-based learning and gamified instruction further enhance this approach by embedding abstract knowledge in real-world problem-solving. When students are in-volved in designing, building, or manipulating spatial elements with a clear purpose, they experience higher motivation, deeper engagement, and greater retention. These methods not only strengthen technical skills but also foster creativity and critical thinking, competencies that are increasingly valued in engineering careers [16].

Although this research is situated in a private university in Lima, the proposed model is adaptable to a wide range of educational settings. The need for spatial reasoning extends beyond the Dynamics course, affecting subjects such as Technical Drawing, Applied Physics, and Design of Mechanical Systems. Therefore, the solutions discussed here aim to be replicable and scalable across disciplines and institutions.

Based on literature and institutional diagnostic assessments, this study hypothesizes that the implementation of technological didactic strategies, particularly those involving AR, 3D printing, and spatial modeling, will significantly improve students' spatial competencies in engineering contexts. Informed by this hypothesis, the objective of the research is to design, implement, and evaluate a set of innovative teaching strategies that effectively strengthen these abilities.

This alignment between theory, pedagogy, and technology defines the framework of the study. Therefore, the present research aims to propose didactic strategies to strengthen spatial competencies in the Dynamics course for engineering students at a private university in Lima.

2. Materials and Methods

2.1. Study Design

This research employed a mixed-methods approach with a quasi-experimental de-sign and pre- and post-intervention measurements. The objective was to evaluate the im-pact of a set of didactic strategies, integrating technologies such as augmented reality, 3D modeling, and isometric visualization, on the development of spatial competencies in engineering students enrolled in the Dynamics course.

The methodological structure aligns with intervention research frameworks in educational settings, allowing for observation of changes before and after pedagogical innovations are introduced. The pre-experimental stage included diagnostic assessments and semi-structured interviews to establish baseline spatial competency levels. The intervention was designed as an educational sequence integrated into the course syllabus, allowing natural incorporation into the academic process without disrupting existing structures.

2.2. Participants and Context

The study was conducted in a private university in Lima, Peru, specifically within the School of Engineering. The target group consisted of 74 undergraduate students enrolled in the Dynamics course during the 2023 academic year. These students belonged to different engineering majors, such as Civil, Mechanical, and Industrial Engineering, and were all in the third or fourth semester of their studies.

Most students had minimal exposure to technical drawing, spatial modeling, or geometry-based tasks in their prior education. The institutional context was characterized by access to digital infrastructure, including mobile devices, computer laboratories, and high-speed internet, which enabled the integration of interactive technological tools. The intervention took place over eight weeks, aligning with the mid-semester curriculum plan, and was embedded within the practical lab component of the course.

2.3. Instruments and Data Collection

Four main instruments were used to gather both qualitative and quantitative data:

- Spatial Ability Test (pre- and post-intervention): A diagnostic tool adapted from established spatial reasoning assessments, including mental rotation, perspective change, and spatial visualization tasks.
- Student Perception Survey: A validated Likert-scale instrument designed to assess students' subjective evaluation of the strategies, their perceived usefulness, and the ease of interacting with spatial content after the intervention.
- Rubrics for Spatial Performance: Used to assess the quality and accuracy of students' technical drawings, isometric sketches, and 3D model outputs.
- Field Notes and Observation Records: Maintained by instructors to document engagement, task resolution patterns, and the dynamics of classroom participation during the intervention.

All instruments were piloted with a previous cohort to ensure clarity and validity. The survey and performance rubrics were revised based on expert judgment and item-level statistical reliability (Cronbach's alpha > 0.80).

2.4.Data Analysis

Quantitative data from the pre- and post-tests were analyzed using descriptive statistics (mean, standard deviation) and inferential techniques such as paired t-tests to determine the significance of observed changes. The effect size was calculated using Cohen’s d. Qualitative data, derived from open-ended survey items and observation records, were analyzed through thematic coding using NVivo software. The codes were grouped into broader categories such as "visualization strategies," "interaction with augmented reality," and "motivation and engagement."

Triangulation was applied across quantitative test results, student perceptions, and classroom observations to reinforce the validity of findings. The overall analysis focused on the improvement of spatial competencies and the pedagogical coherence of the intervention.

2.5. Ethical Considerations

The research followed ethical guidelines established by the host institution’s Re-search Ethics Committee. All participants were informed about the objectives, scope, and voluntary nature of the study and signed informed consent form prior to participation.

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Confidentiality and anonymity were guaranteed throughout the research process. Data collected were used exclusively for academic and research purposes. The intervention posed no risk to the students' grades or academic progression, as it was designed to support their learning rather than evaluate them formally.

3. Results

The implementation of didactic strategies aimed at strengthening spatial competen-cies in engineering students showed significant quantitative and qualitative outcomes. The following subsections present a detailed breakdown of these results, organized into core thematic axes and accompanied by analytical interpretations based on empirical da-ta.

3.1. Pretest and Posttest Results

To evaluate the impact of the intervention, a spatial reasoning test was administered before and after the implementation of didactic strategies. The test included exercises on mental rotation, vector manipulation, and three-dimensional object identification.

Test Type	Mean Score	Standard Deviation	t-value	p-value	Effect Size (Cohen's d)
Pretest	10.3	2.1			
Posttest	15.4	1.9	8.77	< 0.001	1.21

Table 2. Comparison of pretest and posttest results in the Dynamics course.

The data reveals a considerable improvement in students' performance after the intervention, with the average score increasing by more than 5 points. The t-test confirms the statistical significance ($p < 0.001$), and the effect size (Cohen's $d = 1.21$) indicates a strong educational impact. This aligns with studies by Sorby [17] and Maeda et al. [18], who found that structured spatial training significantly enhances students' ability to interpret physical systems and solve engineering problems.

Additionally, the decreased standard deviation in the posttest suggests a more consistent level of spatial skill acquisition across the cohort. These findings support the hypothesis that the integration of hands-on visual tasks and guided cognitive exercises fosters more uniform cognitive development in spatial domains [19,20]. The outcomes con-firm that spatial reasoning, when addressed intentionally, can be taught and developed within a short time frame.

3.2. Technical Progress in Graphic Outputs

Throughout the intervention, students produced technical drawings, vector schemes, and 3D models, all of which were assessed using a four-criteria rubric: spatial orientation,

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proportionality, scale accuracy, and graphic precision. A clear upward trend was observed from the early to the final weeks. Initial scores in "orientation" and "precision" av-eraged below 13/20, indicating poor spatial understanding. By week 8, these dimensions exceeded 17/20, showing mastery of key visual-spatial concepts. These gains align with Duesbury and O'Neil's findings [21], which highlight that iterative exposure to spatial visualization tools enhances both accuracy and conceptual clarity.

The upward trend did not occur in isolation. Peer interaction, use of visual aids, and regular feedback created a learning ecology conducive to deep engagement with spatial content. As spatial concepts became less abstract and more tangible through tools like augmented reality, students were able to shift from mere representation to strategic con-struction of space [22]. This evolution echoes constructivist principles whereby new mental models emerge from experience, trial, and reflection.

3.3. Visual Comparison of Initial and Final Student Products

Two student artifacts, one from the initial and one from the final phase of the intervention, were selected to illustrate the progression in spatial output over time. The side-by-side comparison shows visible advancement in proportionality, accuracy, and spatial reasoning. In the early sketch, planes intersect incorrectly, and the object lacks depth coherence. By contrast, the final version shows mastery of perspective, clean linework, and correct object rotation. This progression demonstrates more than technical improvement; it reflects deeper internalization of spatial frameworks, supported by visual memory training and kinesthetic feedback [23,24].

The example also illustrates the impact of layered instruction: from sketching by hand to building digital models and then refining technical accuracy. Each stage contributed to a metacognitive understanding of spatial operations, echoing the spiral model of learning where complexity is built progressively [25]. Observations by the course instructor corroborated these improvements, noting that students began to articulate spatial logic with greater fluency and autonomy.

3.4. Student Perception and Reflections

Strategy	**% Positive Responses**	**Frequent Comments**
Augmented Reality	92.5%	"I understood the planes better when seeing them projected."
3D Modeling	87.8%	"It helped me imagine how bodies moved in space."
Isometric Sketching	84.3%	"It helped me think in 3D on paper."

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A post-

Vector Simulations	81.6%	"Now vectors make sense in motion."

Table 3. Students' perceptions of implemented strategies.

intervention survey captured students' perceptions regarding the usefulness and impact of the teaching strategies. The survey combined Likert-scale items and open-ended questions.

The overwhelmingly positive responses reveal not only satisfaction but also perceived usefulness in terms of cognitive performance. Augmented reality was especially impactful, confirming earlier research by Fonseca et al. [26], who found that AR environments significantly improve learners' ability to perceive depth, orientation, and structural interaction.

Students emphasized the value of combining digital tools with manual sketching, as the former offered visual clarity and the latter enhanced spatial retention. These findings echo Bower et al. [12], who advocate the use of multimodal instruction to stimulate different cognitive pathways. Qualitative feedback underscores the pedagogical strength of integrative strategies; students did not merely enjoy the tasks; they felt more capable and motivated to face spatial challenges.

3.5. Teacher Observations and Student Autonomy

In parallel with student feedback, the instructor maintained weekly logs recording levels of student autonomy, engagement, and visual reasoning ability. The decrease in requests for direct teacher assistance, from 78% in week 1 to just 22% in week 9, is a strong indicator of cognitive autonomy. Students became progressively more confident in selecting views, building object depth, and verifying spatial logic without instructor intervention. According to the framework of Vygotsky's Zone of Proximal Development [27], this transition marks the shift from dependent to independent mastery.

These findings also point to the success of scaffolding techniques: early support gradually gave way to student-led learning. The instructor noted that by the final stages, many students not only solved complex visual problems independently but also helped peers reconstruct misaligned models, evidence of peer-assisted development and solidification of spatial concepts [14,15]. In line with experiential learning theory, autonomy emerged as a product of active experimentation, feedback, and internalization.

4. Discussion

The outcomes of this study provide compelling evidence that targeted pedagogical strategies, especially those integrating visual technologies, can significantly enhance spatial competencies among engineering students. These results are aligned with global findings in spatial cognition training, where consistent, scaffolded exposure to visual-spatial tasks has been shown to generate lasting improvements in students' academic performance and conceptual clarity [28,29].

The pretest-posttest comparison revealed not only statistical significance but also educational relevance, particularly in courses like Dynamics, where spatial reasoning is foundational to

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understanding mechanical systems. This echoes the work of Sorby [30] and colleagues, who emphasized that spatial skill acquisition is both teachable and predictive of long-term STEM success. In the present study, the magnitude of the effect size (Cohen's $d > 1.2$) places it among high-impact interventions within engineering education literature. Another key aspect of the discussion lies in the effectiveness of multimodal teaching. The integration of augmented reality, isometric sketching, and 3D modeling ad-dressed diverse learning modalities, allowing students to construct mental representations through both analog and digital interfaces. Research by Bower et al. [31] supports this approach, noting that multimodal instruction strengthens neural pathways by en-gaging multiple cognitive systems simultaneously.

Notably, this study also showed a reduction in students' dependency on instructor guidance over time. The sharp decline in help-seeking behaviors across the nine-week intervention suggests an increase in metacognitive awareness and confidence. This is consistent with Vygotsky's theory of proximal development, in which learners gradually internalize tasks initially performed with support [32].

Furthermore, the visual comparison of student artifacts across the intervention period illustrates a shift from representational to structural understanding. Initial sketches showed disoriented perspectives and dimensional inconsistencies, whereas final drawings demonstrated fluency in projection, perspective control, and object manipulation. These results support prior assertions that authentic visual tasks improve abstract reasoning when integrated into curricular design [33,34].

The students' perception survey confirmed the practical relevance of these strategies. More than 90% of participants reported a clearer understanding of spatial dynamics through AR and 3D tools. Interestingly, they emphasized the role of hybrid methodologies, using both sketching and digital simulation, as key to internalizing concepts. Such feedback aligns with the experiential learning cycle, where active manipulation enhances retention and insight [35].

Despite the promising results, several limitations must be acknowledged. The study was conducted in a single institutional context, limiting the generalizability of the findings. Additionally, although the pretest posttest model provides evidence of improvement, it does not isolate which strategy contributed most. Future studies could adopt a factorial design to analyze individual and combined effects of specific tools [36].

Time constraints also posed challenges. Nine weeks was sufficient to see cognitive improvements, but not necessarily to achieve mastery. Longitudinal studies could further track the retention of these skills and their transferability to other engineering contexts. Moreover, future research should incorporate neurocognitive measures or eye-tracking systems to quantify spatial attention shifts during visual tasks [37].

An important pedagogical insight is the students' preference for working collaboratively. Peer interaction in spatial modeling sessions promoted a reflective discourse, where students verbalized their reasoning, corrected misconceptions, and co-constructed spatial solutions. This supports literature emphasizing the role of social interaction in developing higher-order cognitive skills [38,39].

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Finally, while most students benefited, the intervention had varied outcomes depending on students' prior exposure to spatial content. Those with previous training in geometry or design adapted more rapidly. Thus, it is recommended that future curricular planning includes diagnostic assessments of spatial skill levels to personalize support strategies from the outset.

5. Conclusions

This study confirms that spatial reasoning in engineering education can be intentionally developed through well-designed, technology-assisted instructional strategies. By integrating analog drawing, digital modeling, and immersive visualization tools, educators can support the internalization of spatial structures critically for mastering technical subjects such as Dynamics.

The significant improvement in student performance, supported by both quantitative assessments and visual artifacts, highlights the efficacy of multimodal pedagogical frameworks. The study also reveals that students perceive these methods as not only effective but also engaging and confidence-building.

More broadly, this research contributes to the growing body of knowledge that advocates for a shift from purely abstract instruction to experiential, constructivist approaches in STEM education. It demonstrates that when spatial competencies are addressed explicitly, students are better equipped to understand physical systems, communicate technical ideas, and engage in design processes.

For engineering programs, this means rethinking curricular priorities. Reintroducing graphic subjects, investing in accessible visualization technologies, and training faculty in spatial teaching methods are critical steps toward aligning academic preparation with re-al-world professional demands.

Future work should focus on refining the sequence and duration of interventions, expanding the study across institutions, and exploring adaptive learning systems that respond to students' individual spatial profiles. These efforts would support not only academic success but also equity in access to spatial reasoning development.

Ultimately, by prioritizing spatial cognition in engineering instruction, educators can close longstanding gaps in technical comprehension, foster deeper learning, and contribute to the formation of professionals capable of navigating complex, multidimensional challenges in science and technology.

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