Enhancing Tacit Knowledge Construction in Architectural Engineering Education Through 4E Cognition and Virtual Reality

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***Abstract*— This innovative practice paper describes a novel educational framework that combines 4E cognition (embodied, embedded, enactive, and extended) with Virtual Reality (VR) technology to improve tacit knowledge (TK) acquisition in Architectural Engineering Education (AEE). In AEE studio courses, students solve and experience real-world design problems, experiment with solutions, and engage in reflective practices and cognitive processes in collaborative settings. This facilitates the rich development of TK, which includes intuition, practical skills, and lived experiences. However, in theoretical and technical courses, which rely heavily on passive learning of abstract concepts, there is not the same opportunity for students to cultivate TK, resulting in a disconnect between theoretical knowledge and practical applications. This gap can be bridged by leveraging VR's immersive and interactive capabilities, which the 4E cognition principles can strengthen. The 4E cognition emphasizes active learning experiences that mirror the "doing and reflecting" cycle found in AEE studio courses. This synergy between VR and 4E creates an engaging and effective learning environment for students to develop both explicit and tacit knowledge. This approach provides an opportunity for students, digital natives, to improve their intuitive ability to apply, analyze, evaluate, and create architectural knowledge. While only a few studies have used VR environments for AEE, there is no educational framework for designing experiences and sequences that immerse students in their learning processes for TK development. As a result, this paper proposes a VR-based theoretical framework with eight stages for developing immersive and interactive experiences that promote embodied learning, social interaction, and a deeper understanding of theoretical principles. Furthermore, a case study from a structural building course demonstrates how the framework facilitates building TK by simulating scenarios that promote deep cognitive engagement and intuitive problem-solving. This approach aligns with digital natives' learning preferences and aims to provide future architects with both theoretical knowledge and practical, innovative design skills necessary for professional success.**

Keywords*— *Knowledge Construction; Immersive Technology; Design Pedagogy; Cognitive Development; Collaborative Learning

I. Introduction

Tacit knowledge (TK) in architecture is the intuitive understanding gained through experience, enabling skilled architects to make informed design decisions and solve problems [1]. TK is developed through experiences and social interaction in architectural engineering education (AEE). Unlike explicit knowledge, which is like the visible tip of an iceberg (Fig. 1), TK is the submerged part and the "*we know more than we can tell*" aspect of design [2], [3]. In design studio courses, students work on design problems, experiment with solutions, and receive feedback in collaborative learning environments. Through this "doing and reflecting" process, students internalize theoretical concepts and create a diverse body of TK that includes intuition, practical *know-how*, and embodied and social experiences. This promotes a deeper level of understanding and learning in which students intuitively apply, analyze, evaluate, and create knowledge rather than simply recalling facts.

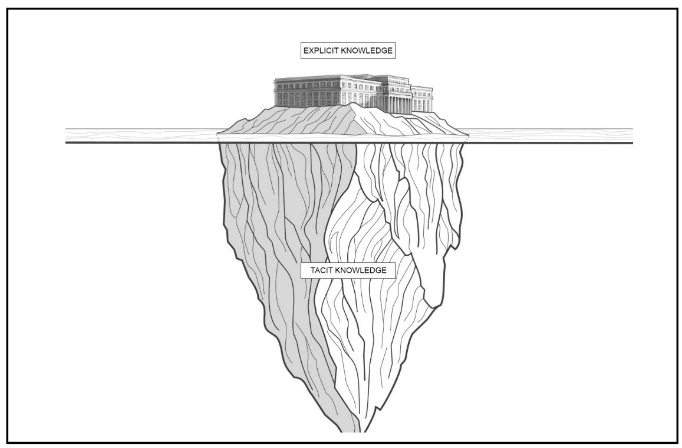

Fig. 1. Knowledge iceberg theory: tacit knowledge, the submerged part of the iceberg, and explicit knowledge, the visible part of the iceberg

However, the reality of AEE paints a disjointed picture. Theoretical and technical courses, representing a significant portion of AEE's curriculum, frequently struggle to cultivate TK due to their emphasis on abstract concepts and passive learning. These courses, which are often limited to lectures, textbooks, and two-dimensional representations, are primarily concerned with explicit knowledge transfer. They are boring to architectural students and disengage them from their studio-based practical knowledge [4]. Unlike design studios, these courses rarely engage students' bodies, senses, cognitive processes, or social interaction, all of which are essential for solidifying knowledge through experience and practice [5]. This can result in a disconnect between theoretical knowledge and its practical application, leaving students with a fragmented understanding of "*what*" to know but no intuitive grasp of "*how*" to translate that knowledge into meaningful design solutions.

On the other hand, Virtual Reality (VR) offers a solution by providing interactive 3D environments for hands-on experience [6], [7]. Research suggests that designing engaging learning experiences that ignite intrinsic motivation and foster collaboration through experience sharing is crucial for TK construction [1]. In this way, VR creates an engaging space for students to collaborate and experience theoretical knowledge in social settings, addressing the lack of motivation often found in traditional courses. Through VR's immersive experience, students can interact with virtual objects, materials, and spaces. Moreover, this approach can be further enriched by incorporating the principles of 4E cognition (embodied, embedded, enacted, extended) [8]. 4E cognition emphasizes how people learn through active engagement with their environment using their bodies (embodied), interaction (enacted), situated knowledge (embedded), and tools (extended). For instance, VR's immersive nature allows students to "walk through" virtual constructions, fostering a more profound understanding through interaction with environments and tools in social settings. Furthermore, using VR for AEE complements the strengths of today's digital natives, who thrive in interactive environments and value the technical and educational aspects more [9], [10].

Although VR has become a key visual tool in architecture, designing experiences for teaching and learning in AEE requires further development, especially for TK acquisition [11], [12]. While some studies have investigated the use of immersive technologies for TK development, particularly in accessibility scenarios, these studies focus on specific situations rather than a process for integrating VR into theoretical courses and TK development. For instance, a study [13] used VR and augmented reality to simulate decision-making scenarios for wheelchair users, helping students apply their implicit knowledge to real challenges. Another study [14] employed VR and mixed reality to evaluate accessibility in small house designs, demonstrating VR's potential to bridge the gap between novice and expert abilities. In this way, a framework that offers integrated experiences for theoretical courses in VR is needed. This would allow students to engage in deeper understanding, experiences, and conversations, enriching their TK construction.

Hence, this paper proposes a VR-based framework in AEE that leverages the 4E cognition principles to create immersive, interactive learning experiences for TK development. Such a framework would allow students to engage with theoretical concepts virtually, enhancing their intuitive and practical skills. The framework's eight stages show how each stage uses VR to promote embodied experiences, social interaction, and a deeper understanding of theoretical concepts. This framework could provide future architects with both explicit and tacit knowledge required for real-world success.

II. Background

A. *Tcait knowledge and Architectural engineering education*

TK is described as embodied, non-verbal, intuitive, and challenging to transfer, among other characteristics of design [15]. Schön [16] critiques the use of technical rationality in architectural education, noting that much of our knowledge in architecture is tacit, evident in our actions and interactions. This knowledge goes beyond academic learning and becomes an essential tool for architectural students. While cognitive perspectives emphasize TK as embodied and internalized through personal experiences, it is also recognized as a collective and co-produced outcome of social interactions [17], [18]. In AEE, TK construction emerges both through self-initiated internal processes and through interactive, socialized activities within the studio's environment. This knowledge is further developed as students engage in critical analysis and dialogue, examining shared ideas from multiple perspectives within collaborative learning spaces. A study suggested the adoption of critical and interactive conversations as a pedagogical tool for TK development in design education [1].

To be more specific, AEE studios excel at creating an essential link between explicit and tacit knowledge through experiential learning. This approach improves students' understanding and cognitive development, in line with Bloom's Taxonomy [19]. Bloom's Taxonomy divides cognitive development into six levels, from basic recall to complex creation, forming a pyramid (Fig. 2) [20]. In studios, students first learn and understand key concepts (Remembering and Understanding) before applying them in critiques, where they analyze, evaluate, and ultimately create innovative designs. This hands-on, reflective learning process is critical for developing the TK that architects require to excel in professional practice. Traditional lectures, however, frequently focus on the transfer of explicit knowledge, emphasizing remembering and understanding concepts. This ignores the critical experiential processes that develop higher-order thinking skills such as Applying, Analyzing, Evaluating, and Creating. Consequently, traditional lectures limit students' ability to translate theoretical knowledge into practical applications, hindering the development of TK.

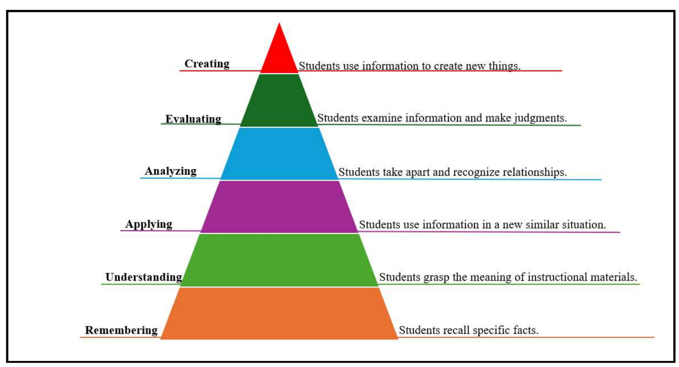

Fig. 2. Bloom’s Taxonomy for the cognitive domains

B. *Virtual Reality and Architectural engineering education*

VR offers AEE unique capabilities due to its immersive and interactive nature. VR environments provide a strong sense of presence, allowing students to feel "in" the space truly [22, 23, 24]. This presence is enhanced by spatial perception, which allows students to not only see the virtual environment but also understand its scale and interact with its spatial components [25, 26, 27]. These interactions deepen immersion and reinforce a student's understanding [27]. In this way, VR excels at transforming abstract architectural concepts into concrete experiences. For instance, students can progress from reading about trusses to virtually manipulating them in 3D to understand their load-bearing capacity and solidify their knowledge.

In fact, this process aligns with Edgar Dale's Cone of Experience theory [28], which proposes a hierarchy of learning effectiveness, with abstract experiences like lectures and readings at the bottom and concrete experiences like simulations and real-world applications at the top (Fig. 3, a). This seminal theory is supported by Fadel et al. [29], who demonstrated that passive learning methods (reading, lectures) are ineffective when compared to active, hands-on approaches. Moreover, Baukal et al. [30] updated and developed this theory with modern multimedia technology and emphasized VR technologies as the most effective learning medium due to their increased presence and immersion (Fig. 3, b). In this regard, VR's dynamic features significantly enhance learning by transforming abstract concepts into interactive experiences, thereby improving cognitive understanding and the educational process across various subjects [31]. VR allows students to actively explore and manipulate architectural elements in a safe virtual space, mimicking the "learning by doing" approach used in studio settings. This active participation fosters a deeper understanding and solidifies abstract architectural concepts into concrete experiences. As a result, for theoretical courses in AEE, VR can immerse students to "*do*" architecture, promoting a more effective and engaging learning experience, which can facilitate TK construction.

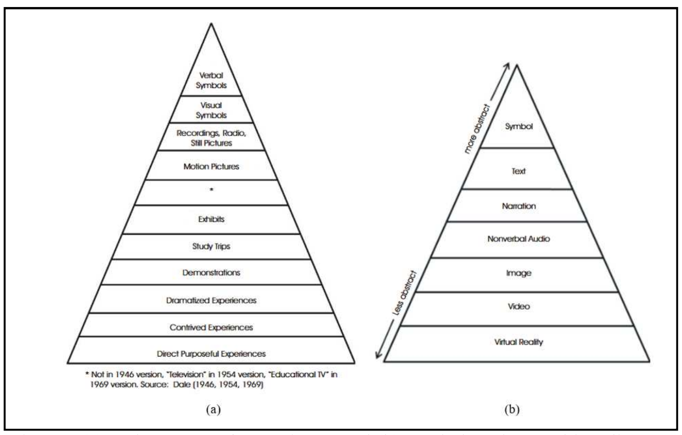

Fig. 3. (a) Dale's Cone of Experience and (b) Baukal et al.'s Multimedia Cone of Abstraction [30].

Several studies demonstrate the effectiveness of VR in transferring abstract concepts into concrete experiences. A study explored transforming traditional paper-based structural engineering lessons into VR experiences. The study showed promise for increasing student engagement and possibly translating abstract engineering concepts into a more concrete, spatial understanding [32]. Moreover, one study used Dale's theory to develop VR training scenarios with varying immersion levels, from audiovisual experiences (low immersion) to hands-on activities (high immersion). The study found a positive correlation between immersion and learning outcomes, suggesting that more immersive experiences lead to concrete experiences [33]. Furthermore, a study used 360-degree panoramic images to demonstrate VR's effectiveness in engaging students with immersive safety scenarios [34]. VR also promotes collaboration in learning processes by enabling rapid prototyping and a deeper grasp of design choices. For example, a study employed VR to create a multi-role training environment where participants collaborated in a simulated setting, taking on specific roles like crane operator, rigger, and signaler. This collaborative role-play transformed abstract knowledge of the crane lift process into a concrete, practical understanding [35]. Hence, these studies highlight VR's ability to simplify complex concepts and enhance cognitive functions such as spatial cognition, memory, and problem-solving. However, a limitation exists in the focus of most research on specific scenarios and student experiences. For theoretical courses, a new framework of different VR experiences, a new cone of experience, is necessary to facilitate the way students construct TK.

C. 4E cognition and Architectural engineering education

Traditional classroom settings often treat the mind as separate from the body, relying on passive knowledge absorption through lectures and textbooks. However, research in cognitive development highlights the crucial role of our physical experience in learning processes [36]. 4E cognition, a theory that emphasizes the embodied, embedded, enactive, and extended nature of cognition, comes into play (Fig. 4). Researchers argued that cognition begins in the body (including the mind) in contexts and then spreads to technological objects and social interactions [37]. In this way, our bodies act as sense-making tools, and our environment provides the context for meaning-making. There is a concise description for each [38]:

1. **Embodied**: This dimension posits that cognition transcends mere mind activities and is intricately intertwined with the entire human physique. It underscores the significance of bodily interactions and sensory perceptions in shaping cognitive processes.
2. **Embedded**: Thinking and understanding are deeply rooted in the surrounding environment. Our cognitive processes do not occur in isolation but are influenced by the contexts in which they happen.
3. **Enacted**: Cognition is perceived as a product of interactions, emphasizing not just internal processing but also our engagement with the external environment.
4. **Extended**: This dimension advocates that cognitive processes can incorporate external elements, such as technologies, other individuals, and tools, broadening the scope of cognition beyond the mind and body.

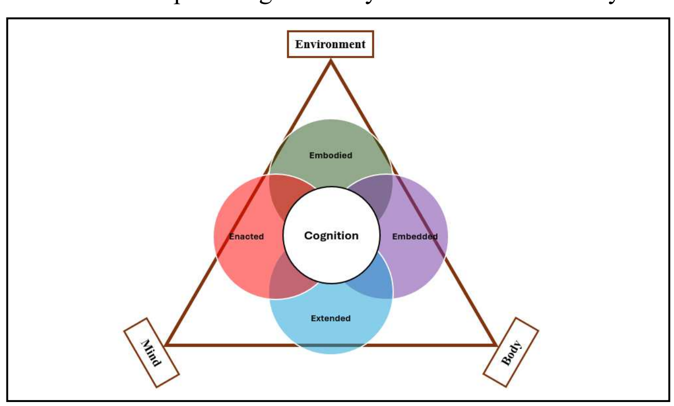

Fig. 4. 4E cognition framework: interaction of body, mind, and environment.

Unfortunately, lecture-based courses in AEE often disregard this cognitive process, leading to knowledge that feels disconnected from practical application. VR, when combined with 4E cognition principles, has the potential to bridge this gap by creating immersive environments where students actively engage with theoretical concepts. This combination can offer an enhanced version of AEE studios, providing a process of hands-on experiences through VR [39]. By actively engaging with these challenges, students unconsciously absorb and refine TK through their cognitive development. This fosters a deeper understanding that goes beyond simply memorizing facts. It cultivates the ability to apply, analyze, evaluate, and create knowledge – all while developing an intuitive grasp of how to use this knowledge in real-world situations. Researchers have recognized VR's effectiveness in education and training through the lens of 4E cognition, calling for focused studies on how these principles can boost learning outcomes [8]. Another study explored the application of 4E principles in VR, advocating for clear identification of these elements to improve VR research clarity and assessment effectiveness [40].

To be more specific, embodied cognition is addressed through VR's ability to immerse learners in simulations where they interact with the environment using their virtual bodies. Embedded cognition is fostered by situating learning within realistic contexts. VR environments can present architectural concepts within simulated historical periods or specific geographic locations, allowing students to grasp the interplay between design and its surroundings. Enactive cognition is facilitated by VR's interactive nature. Students can manipulate virtual elements, experiment with design choices, and observe the consequences in real-time, encouraging active exploration and problem-solving. Finally, VR's extended cognition capabilities allow for the integration of external tools and information displays. Students can access data visualizations, historical references, or collaborative tools within the VR environment, enriching their learning experience and expanding their cognitive resources. Hence, VR experiences with 4E cognition can move beyond simple information delivery in theoretical courses and create a dynamic learning environment that fosters richer cognitive and TK development. This process allows them to develop a personal toolkit of skills and intuition that becomes crucial for success in the field.

III. The Proposed Framework

This study proposes a novel cone of experiences framework for VR-based theoretical courses that incorporates Bloom's Taxonomy and 4E cognition principles. This framework cultivates not only surface-level knowledge but also a concrete understanding of theoretical concepts in both individual and social settings for TK development in AEE. TABLE I shows the details of the eight progressive VR stages, in which students actively engage with the scenarios through cognitive experiences. This multi-layered approach promotes deeper understanding while also encouraging students to apply, analyze, evaluate, and create. By gradually building on these intertwined cognitive processes throughout the VR stages, courses based on this framework could provide students with not only the theoretical foundation but also the practical skills and critical thinking required to construct TK.

TABLE I. Details of the eight progressive VR stages for Cultivating TK in AEE.

Stage	*VR Activity (4E Focus)*	*Bloom's Taxonomy*
1. Foundational Knowledge (Abstract):	**Interactive 3D Glossaries:** Teachers in a VR classroom use virtual tools to present key theoretical concepts. Students walk around and interact with interactive 3D models and animations, and they can access additional information via pop-ups or overlays (*4E*). They can also use virtual whiteboards to further illustrate concepts (*social interactions*).	**Remembering**: Students identify key architectural terms and concepts and connect them to their prior knowledge as they interact with 3D models. **Understanding**: Comprehend the meaning and application of these terms through 3D models and animations.
2. Contextualization (Abstract to Concrete):	**Interactive Virtual Travel:** Students virtually travel through 360° VR environments of iconic buildings or historical structures showcasing applications of theoretical information (e.g., shell structures). They can interact with the 3D models of applications in various ways, such as Rotate, Zoom, and Explode Views (*4E*).	**Understanding and Applying**: Observing 3D model applications in different contexts helps students comprehend how theoretical concepts are applied in real-world architecture. They also learn to apply theoretical knowledge to understand real-world architecture.
3. Immersive Exploration (Transitional):	**Interactive Virtual Walk-through Field Trips:** Students explore various 3D virtual environments depicting different architectural contexts, observing applications, spatial relationships, and performance factors (Embodied and Embedded). They analyze the impacts of different design choices—like material usage and energy efficiency—using overlay data visualizations (Enacted, Extended). Instructors facilitate discussions in these settings to deepen understanding of these design choices (*social interactions*).	**Understanding**: Walking through virtual environments helps students deepen their understanding of the practical applications and spatial relationships of theoretical information. **Analyzing**: Overlaying data visualizations encourages students to break down the relationships between design choices and their impacts. **Evaluating**: Discussion and analysis activities encourage students to assess and critique these relationships and impacts.
4. Interactive Learning Objects (Transitional):	**VR Design Manipulation with Constraints:** Students manipulate a 3D model of a conceptual element, like a roof truss, which includes real-world constraints like site conditions and structural stability (e.g., limited space, material load capacities) (*Embedded*). They adjust model components (beams, connections) in real-time, observing how their design choices affect functionality (*Enacted, Embodied, and Extended*). This safe setting allows experimentation with various design approaches and immediate feedback.	**Applying**: This stage allows students to apply their knowledge to practical scenarios. **Analyzing**: Observing the consequences of their design decisions helps students analyze the feasibility and functionality of their designs.

Stage	*VR Activity (4E Focus)*	*Bloom's Taxonomy*
5. VR Discussion (Concrete):	**Collaborative Virtual Discussion:** Students collaborate to discuss and refine their models from Stage 4, manipulating design elements and employing tools such as virtual pointers and highlighters to improve communication and focus on specific design details (*4E and social interaction*).	**Applying**: Students discuss and apply their knowledge by re-engaging with manipulated models. **Analyzing**: Students can critically assess the effectiveness of various design approaches. **Evaluating**: They also evaluate the practicality and creativity of their peers' solutions.
6. Collaborative VR Design (Concrete):	**Scenario-Based VR Design with Role-Playing:** Students use virtual environments to simulate real-world design scenarios, taking on specific roles to collaboratively create and refine prototypes. This process incorporates theoretical knowledge and real-world constraints, such as site conditions and user needs, along with factors like sunlight and wind (*4E and social interaction*). Through role-playing and data analysis, students discuss, test, and adjust their designs, enhancing their communication, negotiation, and decision-making skills in a collaborative setting.	**Applying**: Role-playing and team collaboration bring theoretical concepts to life in practical design scenarios. **Analyzing**: Collaborative tasks necessitate analyzing design elements under varied conditions. **Evaluating**: Discussion can provide evaluation design solutions based on data and group activities. **Creating**: Students can create and iterate on design prototypes collaboratively.
7. Individualized VR Design (Most Concrete):	**VR Design & Prototyping with Advanced Feedback Loops:** To solve a specific design problem, students work individually to create prototypes that combine theoretical knowledge with real-world and environmental constraints. They use advanced VR tools that provide real-time feedback, allowing them to effectively adjust and refine design elements in a responsive setting (*4E cognition*).	**Applying and Analyzing**: Students apply learned concepts to design challenges, using real-time feedback to analyze and refine their projects. **Evaluating and Creating:** Continuous evaluation and refinement of the design's performance with theoretical and practical parameters to find an innovative architectural solution.
8. Advanced VR Presentations (Most Concrete)	**VR Presentations with User Interaction & Storytelling:** Students present their final designs from the previous stage, interacting with elements and demonstrating functionality. They can use storytelling to explain design decisions and underlying theories. Audiences can experience the designs from a user's perspective (e.g., walking through spaces) and provide interactive feedback.	**Analyzing**: Presenting designs requires analysis of each element to communicate their function and rationale effectively. **Evaluating**: Feedback from audiences and interactive elements in the presentation allow students to evaluate their design's viability and impact.

This VR framework provides a scaffolded learning environment that enhances architectural knowledge and skills for TK development. Despite the internal overlap in 4E cognition's dimensions and Bloom's Taxonomy levels, each stage in this framework targets specific facets of these dimensions and levels. Fig. 5 illustrates the framework, a new cone of experiences, mapping the eight progressive VR stages through the lens of 4E cognition onto Bloom's Taxonomy levels. In the early stages, students work with interactive 3D models and virtual historical explorations to lay a solid conceptual foundation. This interactive approach improves comprehension and piques curiosity (critical thinking) more effectively than traditional methods. They can assess design impacts using data visualizations and discussions in virtual environments, promoting critical evaluation of design decisions. Stage 4's manipulation of VR objects enables students to challenge their new information and immediately see the results of various design strategies in a safe environment, improving their ability to evaluate their decisions critically. This process is essential for subsequent stages that require collaborative problem-solving. In stages 5 and 6, the emphasis shifts to collaborative learning to promote critical conversation and mirror professional architectural settings. Students participate in critical VR discussions with their peers, broadening their analytical perspectives and encouraging the exchange of diverse viewpoints. This collaborative preparation, which includes role-playing as architects, engineers, and clients, helps them understand different stakeholder perspectives while also improving their decision-making and critical thinking skills. Overall, VR activities in stages 3–6 bridge theoretical learning with practical application, developing TK.

In the final stages (7 and 8), students move from collaborative to individualized design, deepening their TK. This crucial transition allows students to critically examine what they learned in previous stages. Stage 7 focuses on personalized VR design tasks with advanced feedback loops that challenge students to apply what they have learned to complex scenarios. Real-time feedback helps improve their analytical skills by immediately showing the impact of their decisions. In Stage 8, students present their final designs in Stage 7, demonstrating functionality and using storytelling to articulate design decisions and theoretical underpinnings. This requires precise analysis and communication of each element's role and effectiveness. Audience feedback and interactive elements during presentations assess the designs' viability and impact, promoting critical thinking and discussion essential for solidifying TK.

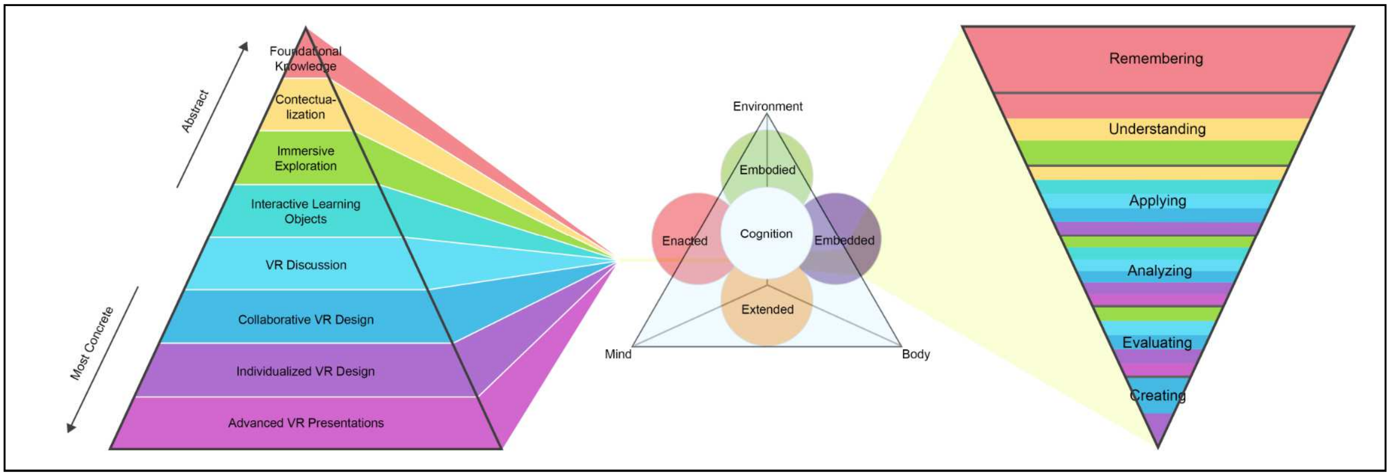

Fig. 5. The new cone of experiences through the lens of 4E cognition onto Bloom's Taxonomy levels.

IV. A CASE STUDY

This case study explores the implementation of the VR framework in a "Structural Analysis and Design" course about suspension bridges within AEE to develop TK. It details the eight VR-based stages designed to enhance students' understanding of structural engineering.

A. Stage 1: Foundational Knowledge:

In a VR classroom, teachers use interactive tools to present key concepts of suspension bridges, such as towers, decks, and loads. Students explore these elements through "Interactive 3D Glossaries" focused on suspension bridge components. For example, students can rotate and zoom to inspect towering structures in detail, including their material composition and internal support systems. Utilize explode views to visualize the internal reinforcements and load distribution mechanisms within the towers. Activate animations to observe from different angles how wind forces are transferred from the main cables to the towers and down to the foundation.

While individual exploration is the primary focus, students can also collaborate in this stage. For instance, students can use annotations highlighting specific elements they find interesting (e.g., highlighting the connection point between a suspender and the deck). Others can observe these annotations, sparking curiosity and prompting further investigation and discussion. Moreover, they could sketch diagrams on a virtual whiteboard comparing the load-bearing capacities of different bridge deck configurations (e.g., cantilever vs. supported sections). Hence, this interactive VR experience allows students to gain a deeper understanding of the key structural components of suspension bridges through exploration, visualization, and collaboration.

B. Stage 2: Contextualization:

Students engage in interactive virtual travel, exploring historical and contemporary suspension bridges using 360° VR panoramas with some interactions that focus on bridge towers. Students cannot walk through the environment, but they can interact with the towers' 3D models. They also can still look up, down, and all around to get a full sense of the bridge's scale. Examples:

1- Golden Gate Bridge (San Francisco, USA): Students are presented with a 360° VR panorama showcasing a breathtaking view of the Golden Gate Bridge from a vantage point near the base of one of the towers (Fig. 6). A detailed 3D model of the tower is provided alongside the panorama. Students can rotate and zoom in on the model to examine the tower's structure in detail. Information hotspots within the VR environment highlight key features like the use of diagonal bracing for stability (enabling students to understand how forces are transferred), as well as the anchoring points for the suspension cables.

Fig. 6. Golden Gate Bridge, San Francisco, USA. Image Source: Public domain, Wikimedia Commons.

2- Akashi Kaikyo Bridge (Kobe, Japan): Students experience a 360° VR panorama showcasing one of the world's tallest suspension bridge towers (Fig. 7). They can rotate a 3D model to observe the towers' aerodynamic shaping, a crucial feature for withstanding strong winds. Information hotspots within the VR environment provide details about the construction methods used to build such a massive structure and the use of seismic dampers to mitigate earthquake effects.

Fig. 7. Akashi Kaikyo Bridge, Kobe, Japan. Image Source: Public domain, Wikimedia Commons.

3- Millennium Bridge (London, UK): Students virtually "stand" near the base of one of the bridge's distinctive tilting towers (Fig. 8). A 3D model of the tower allows exploration of its unique design. Students can rotate the model to understand how the leaning towers utilize tension rods to support the bridge deck, showcasing an alternative approach to suspension bridge design.

Fig. 8. Millennium Bridge, London, UK. Image Source: Public domain, Wikimedia Commons.

In this stage, students gain spatial awareness and a realistic sense of scale from the 360° panoramas, enhancing their grasp of the towers' role in overall bridge architecture. Information hotspots link theoretical knowledge to practical applications, bolstering understanding through embodied cognition. This process can be repeated for other suspension bridges' elements, such as decks and cable configurations. Overall, this VR stage effectively transitions students from abstract concepts to tangible applications, thereby promoting comprehensive understanding through active, immersive learning.

C. Stage 3: Immersive Exploration:

Students can virtually explore and walk through a 3D model of a famous suspension bridge like the Golden Gate Bridge. They can explore its 3D model from various angles to understand the spatial relationships between its structural components—towers, cables, and roadway. This virtual exploration allows them to analyze material usage by examining different elements like steel cables and concrete towers up close. For instance, students can virtually navigate across the bridge's deck, towers, and cables, gaining insights into the scale and spatial dynamics firsthand. They can also modify components to see how different materials affect the bridge's stability. The VR setup includes interactive features like color-coded maps for stress distribution and simulations that demonstrate the impact of wind on the bridge. This stage leverages 4E cognition principles to foster a comprehensive understanding of suspension bridge design.

D. Stage 4: Interactive Learning Objects:

Students manipulate a 3D model of a suspension bridge main cable in VR. The model considers real-world constraints like limited tower placement (site condition) and cable tension capacity (material load). Students can adjust cable thickness, anchor point positions, and pylon heights (Enacted). The VR environment provides visual cues and simulations of cable stress under load (Embedded and Extended). This allows students to experiment with designs and observe the impact on stability (Embodied). This allows them to analyze the trade-offs between different suspension bridge designs.

E. Stage 5: VR Discussion:

Students revisit their bridge models from Stage 4, manipulating them again while discussing and refining designs in group settings. Teachers guide the discussion to analyze, critique, and iterate on their suspension bridge designs. For instance, students can use highlighting tools to adjust specific elements like cable segments, enhance communication, and focus on design modifications. They can adjust cable thickness, anchor points, or pylon heights in VR, allowing immediate visualization of the impact. Students can also load multiple variations of the bridge model (e.g., thicker cables vs. higher pylons) to compare stability and stress distribution under the same load conditions. These activities promote critical thinking and discussion, which are integral to the 4E cognition to facilitate TK development.

F. Stage 6: Collaborative VR Design with Role-Playing:

In this stage, students engage in a scenario-based activity to design a suspension bridge in a VR environment that simulates real-world conditions. In this VR simulation, students adopt specific roles: an Architect focuses on aesthetics and functionality, considering pedestrian pathways and visual impact; a Structural Engineer ensures stability, analyzing forces and load distribution; and a Client assesses user needs, potential maintenance requirements, and pedestrian safety features. The VR setup allows students to manipulate bridge spans, cable configurations, and pylon designs, adjusting for factors like wind load and traffic flow. A virtual wind tunnel helps students study the aerodynamic effects on the bridge, with real-time visualizations showing wind flow. Students can highlight specific bridge components in VR and discuss their rationale behind design choices. This interactive environment promotes critical thinking and problem-solving as students discuss and justify their design decisions, exploring the balance between structural integrity, aesthetics, and functionality. This stage underscores the importance of collaboration, critical discussion, and practical application of theoretical knowledge in addressing real-world challenges.

G. Stage 7: Individualized VR Design & Prototyping:

In this stage, students design a suspension pedestrian bridge within a VR environment, such as a park with a river. They select bridge components and materials with real-world properties—weight, strength—from a virtual library and test different spans, heights, and geometries to fit environmental and design constraints. Students experiment with various bridge configurations, like straight or curved shapes and cable setups, observing their impacts on structural stability through real-time VR simulations. These simulations display stress distribution under different loads (e.g., wind load), enabling an iterative design process. Immediate feedback from the simulations allows students to refine their designs, enhancing stability and aesthetics continually. For instance, simulations that show high-stress areas prompt students to alter the bridge's geometry or add support, enhancing stability. This stage not only enables the application of theoretical knowledge but also cultivates advanced design thinking and problem-solving skills, as students receive immediate feedback and understand the complex interplay between form, function, and structural integrity in bridge design.

H. Stage 8: Advanced VR Design Presentations:

In this final stage, students present their designs from stage 7 within the VR environment. They are positioned alongside their virtual bridge, allowing the audience to walk through and interact with the structure. They use annotation tools to highlight design elements and explain their choices for materials, cable configurations, and support structures. Visual aids illustrate key considerations and design iterations. Furthermore, students demonstrate the bridge's structural integrity through real-time simulations of stress distribution under various conditions. Audiences are encouraged to initiate conversations, walk through the bridge to inspect details closely, and provide feedback on aesthetics, functionality, and user experience. This interactive approach allows students to effectively communicate their design process and the structural integrity of their bridge, transforming a traditional presentation into an interactive and immersive experience.

I. Evaluation:

Firstly, pre- and post-course assessments and interviews gauge students' grasp of suspension bridge concepts using multiple-choice questions, VR design simulations, and short essays and conversations. Moreover, expert evaluations assess student projects and understanding in the presentation stage. For instance, bridge engineers and industry professionals review creativity, problem-solving skills, and the practical application of theoretical knowledge, particularly examining structural integrity and compliance with real-world constraints. During final presentations, students interact with their VR designs and explain their theoretical approaches, allowing experts to assess technical soundness, adherence to constraints, functionality, and depth of TK through probing questions about design choices.

V. SUMMARY AND RECOMMENDATION

This paper has explored the limitations of theoretical AEE courses in fostering TK acquisition. While studio environments effectively cultivate TK through hands-on experiences and social interaction, theoretical courses often rely on passive learning methods that fail to bridge the gap between theoretical knowledge and practical application. This disconnect can leave students with a fragmented understanding and hinder their ability to apply theoretical concepts to real-world design challenges intuitively. To address this gap, this study proposes a novel framework as a new cone of experience, which leverages VR technology and the principles of 4E cognition to create immersive and interactive learning experiences in theoretical AEE courses. The framework outlines eight progressive stages, each designed to utilize VR's capabilities and 4E cognition principles to achieve specific cognitive domains aligned with Bloom's Taxonomy. The early stages focus on building a foundation through interactive 3D models and virtual explorations, fostering comprehension and critical thinking. Subsequent stages introduce design manipulation, collaborative discussions, and scenario-based role-playing, gradually promoting analysis, evaluation, and creation of design solutions as well as critical conversations. Finally, the framework encourages students to apply their knowledge and refined TK through individual design tasks and presentations that require them to analyze their design choices and communicate their rationale effectively and critically. Hence, these stages are scaffolded to develop both explicit and tacit knowledge, helping students learn and apply theoretical concepts in practice. This method suits digital natives, who thrive in interactive, technology-rich learning environments.

While this paper presents a theoretical framework, further research is needed to evaluate its effectiveness in promoting TK development in AEE settings. Here are some key recommendations for future studies:

- **Empirical studies:** Controlled experiments comparing the effectiveness of the VR framework to traditional methods in fostering TK acquisition should be conducted. Pre- and post-intervention assessments, along with qualitative feedback from students and educators, would provide valuable insights into the practical impacts of this educational approach.
- **Longitudinal studies:** It is crucial to investigate the long-term impact of the VR framework on students' professional practice and their ability to apply TK in real-world scenarios.
- **Addressing Implementation Challenges:** It would be beneficial to explore potential challenges associated with VR implementation in the classroom, such as student comfort with the technology, the possibility of motion sickness, and instructor training needs.
- **Social interaction evaluation:** Studies are needed to assess how effectively VR fosters collaboration, communication, and knowledge sharing across the framework's various stages.

Furthermore, the framework's adaptability invites exploration beyond AEE. Similar frameworks could be developed for other engineering disciplines or design fields where fostering TK is crucial. By embracing VR technology and 4E cognition principles, educational institutions can create more immersive and engaging learning environments that empower students to develop the knowledge and skills they need to excel in a rapidly evolving world.

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