MetaClues: Constructivist Learning via Progressive Clues from Generative AI in a Metaverse Environment

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***Abstract*—This paper introduces MetaClues, an AI-driven framework that integrates generative AI and Metaverse technology to deliver a constructivist learning experience. This innovative system combines image-to-3D generation, large language models, and text-to-image diffusion models to create progressive clues within a virtual campus. Learners engage in thematic zones, interact with AI-powered non-playable characters, and manipulate artifact items—creating, fusing, or exchanging them—to steer their own discovery process.**

At the heart of MetaClues is the goal of uncovering or recreating a secret artifact, a multidisciplinary item rich with educational significance. Learners follow progressive clues tied to a relevance score for each item they possess. This scoring system evaluates an item's connection to the secret artifact across multiple dimensions, offering insights into its value. To unlock additional clues, learners must create, fuse, or exchange items, refining their understanding of the artifact based on these scores. This adaptive approach strikes a balance between structured, domain-specific learning and open-ended creativity, fostering active engagement.

A pilot study with 19 participants showed notable improvements in participation, knowledge retention, and motivation to explore further. Impressively, 84% of novice learners gained a substantive understanding of multidisciplinary concepts. Evaluations using the System Usability Scale (SUS) and the Technology Acceptance Model (TAM) confirmed high usability and educational impact.

Using generative AI as a collaborative tool, MetaClues transforms learners from passive recipients into creative problem solvers. Our research highlights its success in applying constructivist principles, blending generative AI and immersive technology to enrich multidisciplinary education.

***Index Terms*—metaverse, constructivist learning, generative AI**

I. Introduction

Constructivist learning environments emphasize active knowledge construction through authentic experiences and social collaboration [1]–[4]. These principles align naturally with immersive technologies, which engage learners and foster creativity. Recent advances in large language models (LLMs) and diffusion-based image generation tools enable dynamic creation of text and visuals, enhancing shared virtual settings—often called Metaverse environments. Studies show generative AI in teacher training improves higher-order thinking skills [5], while LLMs offer valuable educational opportunities and instant feedback [6]. Together, these insights highlight the potential of AI-driven environments to empower creative engagement.

This paper introduces MetaClues, a framework that leverages these technological advances to support constructivist learning within a virtual campus. By integrating generative AI and Metaverse technology, MetaClues empowers learners to explore, create, and collaborate, balancing structured domain knowledge with open-ended discovery.

A. MetaClues Framework

We propose MetaClues, a multi-device Metaverse framework set in a virtual campus, integrating generative AI, gamification, and collaborative exploration to advance constructivist learning. This system reimagines education by enabling learners to reconstruct multidisciplinary artifacts—such as historical objects—through AI-generated 3D models, real-world photographs, and peer contributions. Multi-modal large language models (LLMs) provide contextual feedback, guiding learners without dictating solutions, while a novel relevance metric evaluates creations based on cultural significance and geometric similarity rather than strict accuracy. This approach balances domain-specific knowledge with creative discovery, fostering active engagement across fields like history and cultural studies.

MetaClues supports constructivist principles by encouraging self-directed exploration of artifacts, multi-perspective analysis through AI-assisted iteration, and social collaboration in hybrid virtual-physical spaces. Rarely explored in multidisciplinary contexts, this framework leverages generative AI to spark innovative, gamified learning experiences. It offers two primary contributions:

1) **AI-Metaverse Integration**: Combines generative AI (image-to-text, text-to-text, text-to-image, and image-to-3D process) within an immersive constructivist environment, supporting interactive and creative learning.

2) **Novel Item Evaluation Mechanism**: A relevance metric that values creative alignment with secret artifacts over traditional accuracy, rewarding both precision and imaginative interpretation.

B. Pedagogical Alignment

MetaClues aligns with the seven pedagogical goals of constructivist learning [7] through its core design:

1) **Knowledge Construction**: Learners devise autonomous strategies (e.g., web research, AI querying, real-world photography) to reconstruct artifacts, such as historical objects in our preliminary study.
2) **Multi-Perspective Analysis**: The relevance metric encourages diverse approaches by assessing creations for cultural and geometric relevance rather than a single correct answer.
3) **Real-World Contextualization**: Combining physical photographs with AI-generated 3D models connects virtual exploration to tangible contexts.
4) **Student Ownership**: Learners drive artifact reconstruction and share discoveries, shaping their own learning paths.
5) **Social Collaboration**: Hybrid virtual-physical spaces facilitate peer interaction, both in-person and online.
6) **Multi-Modal Representation**: Cross-device tools integrate 3D modeling, textual LLM feedback, and gamified clues for a rich learning experience.
7) **Metacognitive Reflection**: Progressive relevance scores and LLM guidance help learners assess and refine their strategies.

C. Application and Impact

In a user study, students uncover a secret artifact with educational value by generating and fusing items, guided by LLM feedback. MetaClues aims to deepen conceptual understanding—whether in history, cultural studies, or beyond—while sparking creative thinking through iterative artifact creation. Leveraging gamification's motivational power [8], [9] and immersive settings [4], [10], [11], it balances structured learning with exploration.

By positioning generative AI as a co-constructor rather than an authority, MetaClues shifts learners from passive consumers to active investigators. Initial trials show students debating evidence, negotiating strategies, and recontextualizing cultural knowledge—embodying a transition from instructionist to constructivist education [1]. This proves especially effective for complex domains like cultural studies, where understanding emerges from reconciling fragmented evidence across physical and digital contexts.

II. Related Work

A. Gamification with Constructivist Learning

Contemporary gamification strategies in education often prioritize quantifiable engagement metrics over deeper cognitive processes [4], [12], creating tension with constructivist principles of student-driven knowledge construction. While gamification mechanisms boost student motivation and collaboration [8], [9], they risk reducing learning to transactional task completion rather than fostering reflective inquiry.

Our framework addresses this gap by implementing constructivist goals: **(1)** knowledge construction through AI-assisted artifact creation, **(2)** multi-perspective appreciation and metacognitive reflection through progressive and iterative multi-faceted assessments. Unlike leaderboard-driven systems, our assessment metric rewards creative thinking and understanding rather than rote memorization, aligning with constructivist theory's "appreciation for multiple perspectives" [1]. The integration of AI as a non-intrusive co-designer [13], [14] maintains learner ownership by enabling students to blend AI-generated suggestions with personal insights rather than following prescriptive solutions.

B. Generative AI for Creative Interaction

Generative AI's role in gamified learning intersects with seven constructivist learning pedagogical goals. Recent advances in generative techniques—from text-to-image models to AI-driven item manipulation—have broadened creative possibilities in educational contexts. Previous research on integrating generative AI into XR environments [15] demonstrates that merging AI-driven content with immersive interfaces can foster collaborative creativity and accelerate learning-by-doing. While previous approaches highlight novel human-machine co-creation paradigms, many have focused on either artistic exploration or professional workflows, rather than explicit learning objectives and performance metrics aligned with formal education.

Our framework builds on this foundation but emphasizes educational outcomes, leveraging generative AI to scaffold specific learning goals across multiple domains. By positioning generative models as exploratory partners rather than authority figures, we enable the "active reconciliation of new and prior knowledge" fundamental to constructivist theory [1]. MetaClues inverts this dynamic—making AI a means for students to manifest evolving mental models through cyclical interaction between digital creation and real-world input [2], [4]. This approach aligns with experiential learning principles [2], [4] while avoiding LLM reliability concerns [6] by emphasizing the value of the iteration process over producing correct outputs.

C. XR, VR, and Metaverse-Based Learning

Contemporary gamification strategies in education often prioritize quantifiable engagement metrics (points, badges, number of tasks completed) over deeper cognitive processes [4], [12], in conflict with constructivist principles of student-driven knowledge construction and multiperspective evaluation. Although such mechanisms significantly boost student motivation and social collaboration, as evidenced in various e-learning contexts [8], [9], they risk reducing learning to transactional task completion rather than fostering reflective, iterative inquiry central to constructivist pedagogy. However, many Metaverse implementations prioritize immersive fidelity over pedagogical design [15]–[17], even though constructivist research emphasizes integrating realistic contexts, social experiences, and multi-device exploration [1].

MetaClues extends beyond domain-specific XR or VR learning systems by embedding all seven constructivist goals in its architecture. The framework addresses this gap by directly implementing constructivist goals, including: (1) *knowledge construction* through AI-assisted artifact creation, (2) *multi-perspective appreciation* via embedded semantic similarity metrics, and (3) *metacognitive reflection* through progressive multi-faceted assessment feedback as clues for solving the riddle.

This approach builds on VR studies demonstrating that contextual feedback improves conceptual understanding [12], but extends it by using various generative AI models to quantify not just task completion, but the richness of learners' creative pathways. Unlike leaderboard-driven systems, our assessment metric rewards motivate users to think and understand, rather than rote memorization, aligned with Constructivist Learning Theory [1] "appreciation for multiple perspectives," where learners iteratively refine hypotheses about historical artifacts through generative experimentation. The integration of AI as a non-intrusive co-designer [13], [14], further embodies constructivist ideals by maintaining learner ownership—students blend AI-generated suggestions with personal insights rather than following prescriptive solutions. MetaClues moves Metaverse-based learning from passive immersion to active knowledge construction.

III. System Architecture

In this section, we present the system architecture that underpins MetaClues framework, highlighting how multiple generative AI modules are integrated into an interactive Metaverse platform. By merging these modules—image-to-3D generation, multi-modal large language model (LLM), reasoning LLM, and an evaluation scoring subsystem—our framework fosters real-time, gamified learning experiences (Figure 1).

A. Framework Overview

1) **Multi-modal LLM-Based Generation**
Two distinct LLM processes support the system: image-to-text generation and text-based fusion. For new items, a multi-modal LLM analyzes user-uploaded images to generate contextually rich titles and descriptions. For item fusion, a reasoning LLM creatively combines attributes from two existing items to create a new item.
2) **Text-to-Image Generation using Flux**
Creates high-fidelity, 2D visualizations of newly fused generated items. This component leverages Flux models, providing immediate visual feedback on how the AI envisions the creative fusion.
3) **Image-to-3D Model Generation using Hunyuan3D**
Both user-uploaded images (in the creation pipeline) and AI-generated images (in the fusion pipeline) are transformed into three-dimensional models using the Hunyuan3D synthesis system. This creates interactive 3D representations (GLB files) that learners can manipulate within the Metaverse environment.
4) **LLM-Based Assessment via Multi-faceted Scoring**
Implements a reasoning LLM to assess semantic similarity between the user's item's descriptions and the secret artifact description. A higher similarity score denotes closer replication that guides learners through progressive clues, driving the discovery process.
5) **Metaverse Interface**
Offers a multiplayer environment in which students navigate and interact in real time. They upload images, fused items, receive newly fused items with an evaluation score as feedback, and observe their creations in an immersive, shared virtual setting.

B. Detailed Pipeline of Item Creation

The item creation pipeline involves several key steps. First, learners upload a 2D image, which is then processed by a vision LLM (`llama3.2-vision`) to generate a concise title and 30-50 word description:

1) Learners upload an image from a mobile or desktop computer with a web interface.
2) A new title and description are generated using a predesigned system prompt that identifies the image content and adds extra contextual meaning via a reasoning LLM (`deepseek-r1-jp:14b-8k`).
3) The Hunyuan3D model generates a 3D representation of the item (`.glb` format) using the same image, ensuring that both visual and textual data are captured.
4) A rating is computed by comparing the newly generated item with a secret artifact using a reasoning LLM (`deepseek-r1-jp:14b-8k`).

Figure 2 illustrates our item creation pipeline.

C. Detailed Pipeline of Item Fusion

In the item-fusion pipeline, users combine two existing items to create a new fused item. The system employs a specialized prompt to extract and integrate the textual attributes of both items, resulting in a new title and description:

1) Users select two existing items from their inventory.
2) A new title and description are generated using a predesigned system prompt that leverages the reasoning capabilities of (`deepseek-r1-jp:14b-8k`) to capture the essence of both items.
3) The (`Flux`) text-to-image model is applied to produce an image that visualizes the fused item.
4) Hunyuan3D generates a new 3D model from the image, resulting in a 3D (`.glb`) file.
5) A rating is computed to assess the relevance of the fused item to a secret item.

Figure 3 illustrates our item fusion pipeline.

D. Multi-Faceted Item Evaluation and Rating

Each new or fused item undergoes a comprehensive evaluation process, automatically rating its relevance on a 0-10 scale

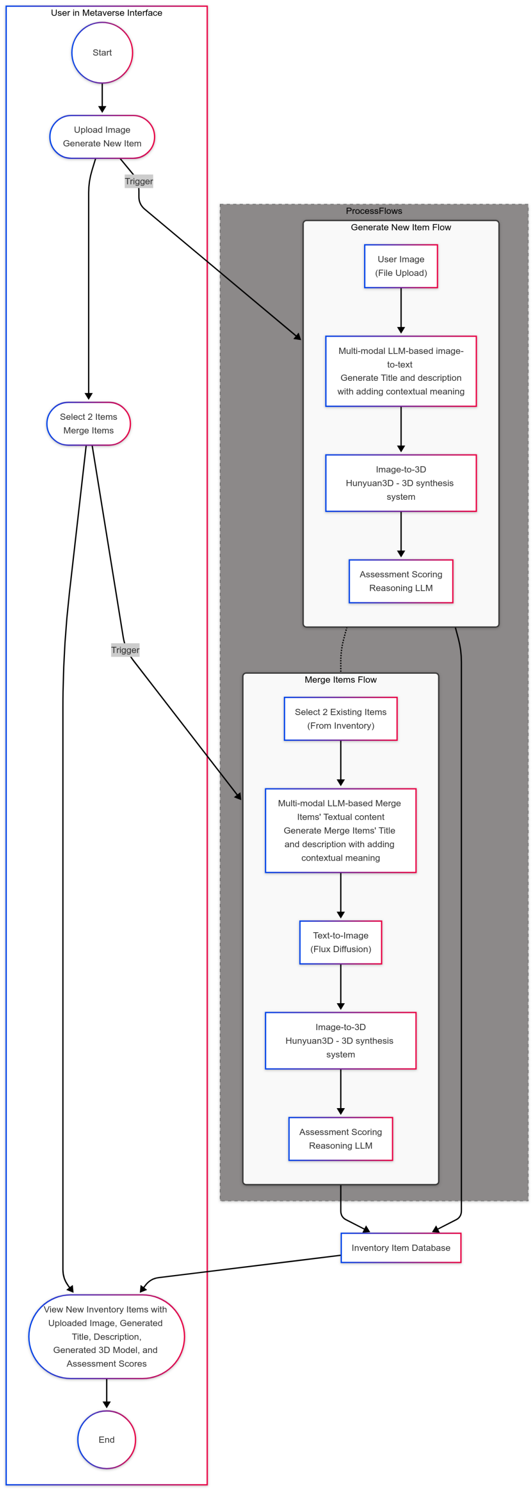

Fig. 1. Overall architecture of the MetaClues framework, integrating multiple AI modules (LLM-based image-to-text and text-to-text, image-to-3D, Disffusion Model-based text-to-image, and reasoning LLM-based assessment scoring) into a campus-based Metaverse environment for gamified education.

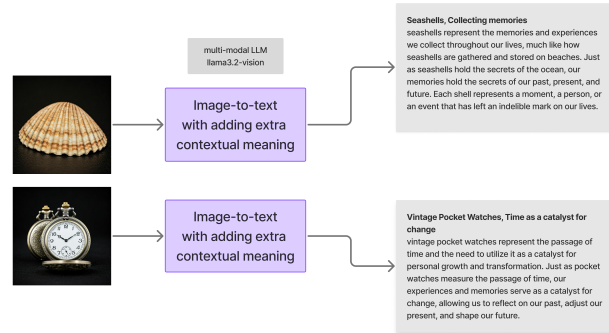

Fig. 2. Item Creation: A new title and description are generated via a pre-designed system prompt that identifies the user uploaded image content and adds extra contextual meaning

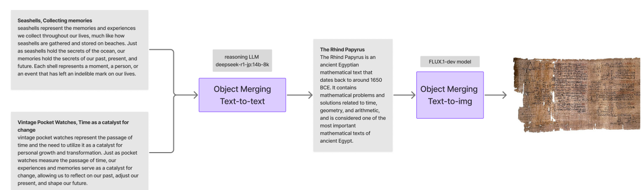

Fig. 3. Item Fusion - A text-to-image diffusion model to visualize the fused description

using a reasoning LLM (`deepseek-r1-jp:14b-8k`). This rating is then categorized into one of five levels:

Normal (N), **Rare (R)**, **Super Rare (SR)**, **Super Super Rare (SSR)**, or **Ultra Rare (UR)**

This rating information is stored in the user's inventory for future reference and can be used to inform further fusions.

The item also stores a star rating, which serves as an immediate assessment for measuring its semantic proximity to the secret item. This is achieved through a multi-modal analysis by a LLM (`llama3.2-vision`), which evaluates the item's descriptors against the reference content of the secret artifact.

Our rating scale is based on a 0 to 10 star system, providing a nuanced evaluation of each item's level of rarity. This feedback loop is designed to motivate users to strike a balance between faithful replication and creative divergence, driving them to explore historical and cultural items in depth.

IV. MetaClues: A Constructivist and Gamified Learning Framework

The MetaClues framework merges generative AI and a gamified Metaverse environment to create a virtual campus that reimagines education through constructivist principles and interactive exploration. Grounded in the seven pedagogical goals of constructivist learning [7] and inspired by insights from immersive gamified systems [4], [15]–[17], MetaClues transforms learners into active co-creators of knowledge. Set in a virtual campus, this framework leverages AI-driven tools—such as image-to-3D conversion (Hunyuan3D), text generation (`llama3.2-vision`), and a reasoning LLM (`deepseek-r1-jp:14b-8k`)—to foster creativity, collaboration, and contextual understanding across disciplines like history and cultural studies.

A. Core Pillars of Constructivist Design

MetaClues extends constructivist learning through three integrated pillars, each supporting specific pedagogical goals (Figure 4).

1) **Active Knowledge Construction** (Goals 1,7): Learners photograph real-world objects, convert them into virtual 3D models, and iteratively refine them using AI-generated feedback. A multi-faceted scoring mechanism provides progressive clues—assessing relevance to a secret artifact - prompting reflection and adaptation rather than aiming for exact replication. This cycle of assimilation and accommodation deepens understanding through personalized exploration.
2) **Multi-Perspective Negotiation** (Goals 2, 5): The Metaverse campus facilitates collaboration via shared spaces, item fusion mechanics, and peer-to-peer item exchanges. Customizable avatars and specialized NPCs—such as the History Tutor, Arts & Technology Tutor, and Computer Science (AI) Tutor—guide learners in fusing items with distinct styles (e.g., historical, futuristic, surrealistic), encouraging diverse creative strategies and social interaction.
3) **Contextual Embodiment** (Goals 3, 6): Mixed-reality interactions bridge physical and virtual realms. Learners upload real-world images to generate 3D items, blending them into a realistic yet novel campus environment (Figures 5 and 6). Cross-device fluency (mobile/desktop photo uploads to VR gameplay) ensures a multi-modal experience that anchors learning in authentic contexts.

B. Gamified Exploration in a Virtual Campus

MetaClues materializes constructivist learning as a gamified sandbox, where students roam thematic zones, interact with AI-enabled NPCs (Figures 5 and 6), and pursue the replication of a secret artifact through riddles and clues. The technical pipeline of the framework (Figure 7) supports this process:

1) Authentic Context and Exploration (Goal 3): The virtual campus mirrors a real-world setting, embedding artifact riddles in familiar yet innovative spaces. Learners gather real-world images, convert them into items, and explore freely, merging physical and virtual experiences.
2) Social and Collaborative Play (Goal 5): NPCs offer unique interactions—scanning historical data, fusing item attributes, or providing textual prompts—while peer exchanges enable collaborative reinterpretation. This fosters a social learning ecosystem that balances competition and cooperation.
3) Ownership and Iterative Design (Goal 4): Each learner maintains a unique inventory of created items (images, descriptions, 3D models), tailoring their approach to solving the artifact puzzle. Alternative solutions are rewarded, as the scoring system values creative alignment over strict accuracy.
4) Assessment and Feedback (Goals 1, 2, 7): A reasoning LLM calculates relevance scores based on conceptual and visual similarity to the secret artifact. For example, with Dürer's Rhinoceros (Figure 8), high scores can stem from faithful reproductions or imaginative deviations, promoting multi-perspective analysis and gamified motivation.

C. Educational Impact and Outcomes

MetaClues elevates conventional learning by embedding it in a creation-driven, gamified Metaverse. Students engage deeply through iterative item generation and NPC-led exploration, toggling between interpretive fidelity and creative innovation. Immediate feedback via relevance scores strengthens knowledge retention, while the visually rich setting fosters curiosity and problem-solving. This synergy of AI-driven generation and a structured campus environment bridges modern technology with classical narratives, offering a deeper educational impact adaptable to diverse disciplines.

V. Preliminary User Study

A preliminary user study was conducted with 19 university students from various academic disciplines.

A. Study Design

Participants engaged in a creative task: uncovering a secret historical artifact, which were designated by an educational staff. In this study, an item from the early Renaissance is chosen (specifically, Dürer's Rhinoceros in Figure 8). Learners receive partial textual clue, a riddle referencing the artifact's historical context:

> *Sample Riddle Clue:*
> **I am an armored beast from lands unknown,**
> **With a single horn and plates of stone.**
> **Born of a 16th-century artist's imagination,**
> **A traveler's tale became my creation.**

In addition to the riddle, learners received additional background hints that supplied further historical or cultural context, thereby helping them understand the significance of the artifact.

B. Measurement Instruments

Three questionnaires were developed for this user study:

1) Pre-Questionnaire: Participant demographics, background knowledge of the secret artifact, and technological familiarity.
2) Post-Questionnaire: System Usability Scale (SUS) [18] and Technology Acceptance Model (TAM) [19] measuring perceived usefulness (PU) and ease of use (PE).
3) Post-Questionnaire: MetaClues-specific evaluation of four framework pillars: Constructivist Virtual Campus, Active Exploration, Artifact Replication, and a Multi-Faceted Assessment.

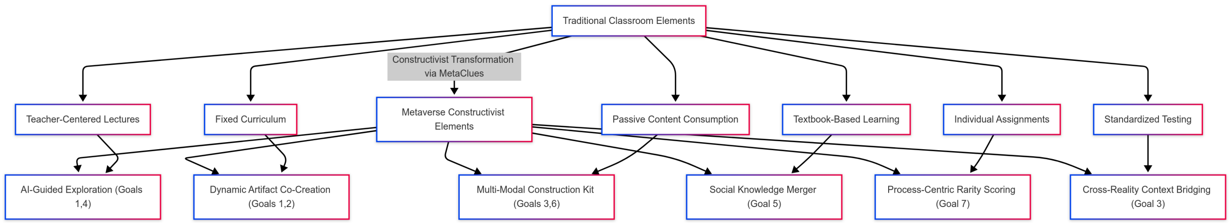

Fig. 4. Pedagogical transformation from traditional classroom to MetaClues's constructivist Metaverse environment

Fig. 5. Virtual campus: Main area with History Tutor NPC

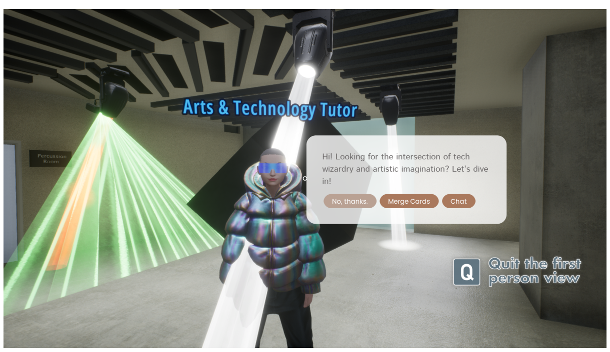

Fig. 6. Virtual campus: Area with Arts & Technology Tutor NPC

We used different response formats for the pre-questionnaire and post-questionnaire, including the 5-point Likert scale (1 = Strongly disagree, 5 = Strongly agree), multiple choice, and free text.

C. Revealing the Secret Item

At the conclusion of the pilot session, all learners submitted their final items. The host then revealed the secret artifact in a culminating sequence:

1) **Educational Context**
Learners gained insight into how Albrecht Dürer, a renowned Renaissance artist, created his iconic rhino depiction without direct visual references. This educational context highlighted the historical significance, cultural context, and printing technology of printmaking that Dürer employed. Additionally, students recognized the similarities in our star rating and interpretive style between their own submissions and the canonical artifact, fostering a novel form of creative and puzzle-like learning.

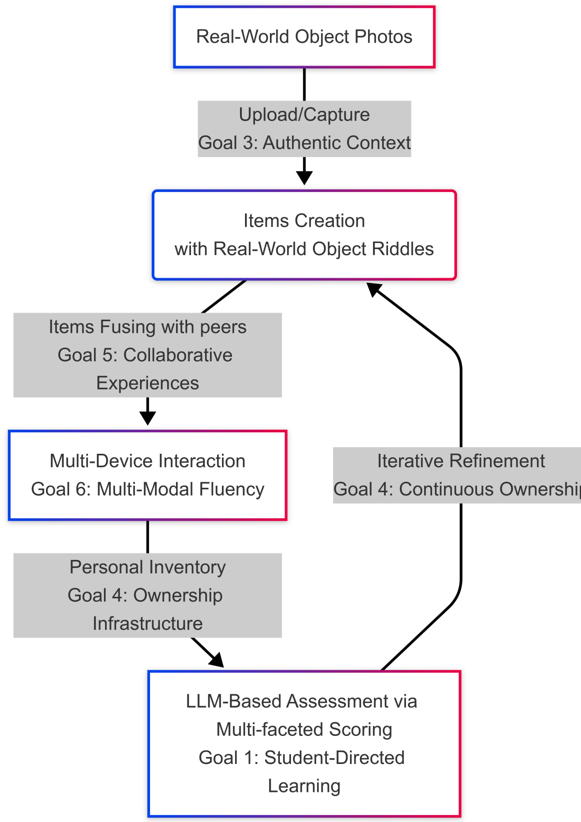

Fig. 7. Constructivist learning loop in MetaClues's technical pipeline

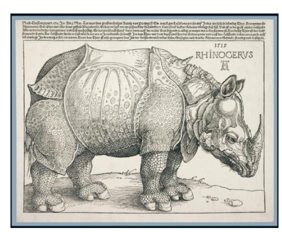

Fig. 8. The secret artifact: Dürer's Rhinoceros

2) **Reflection on System's Feedback**
The platform provided feedback on how closely or creatively the learners' final submission compared to

the canonical artifact. This closing reflection encouraged meta-cognitive thinking: how the system's generative tools facilitated their interpretation or replication of an item with incomplete data.

VI. Analysis of Pre-Questionnaire Results

Before using the system, participants completed a short survey on demographics and prior familiarity with digital games, Metaverse experiences, and historical items.

An analysis of demographic data shows that most participants (84.21%) are Computer Science majors (Computing & Software, AI, or Business Computing and Data Analytics), with smaller proportions from Communication (5.26%), while the remainder study interdisciplinary programs. Almost all of the participants (94. 74%) were between 18 and 24 years old. Approximately half (52.63%) indicated that they played digital PC games frequently or very frequently, suggesting moderate familiarity with the digital gaming experience. Regarding historical items, 47.37% reported no familiarity and an additional 42.11% indicated only slight familiarity, highlighting a limited baseline understanding. These findings suggest that the sample, characterized by novice-level historical knowledge, was well-suited to evaluate the potential of the MetaClues framework in enhancing domain-specific understanding.

VII. Analysis of Post-Questionnaire Results

After using the MetaClues environment, participants completed the post-questionnaire that included the SUS (System Usability Scale) and TAM (Technology Acceptance Model), along with a custom evaluation on the four pillars of the MetaClues framework. The SUS **(mean=3.72)** reflected moderate-to-high usability, while TAM yielded favorable **Perceived Usefulness (mean=3.82)** and **Perceived Ease of Use (mean=3.79)**. Notably, **84.48%** self-reported *novice-level familiarity* with the historical domain, but most of the participants found the platform user-friendly and motivating for exploring the secret artifact.

MetaClues-based evaluation further confirmed that the unique elements of constructivist learning on the virtual campus, active exploration, artifact replication, and multi-faceted assessment were well received. Participants noted that fusion mechanics and open-ended navigation foster creative experimentation and improved their understanding of historical artifacts. The **Reinforced Active Exploration** scores (mean $\sim$3.95) imply that allowing users to experiment with item fusion contributes to **divergent thinking** and fosters curiosity. Participants scored **Artifact Replication** (mean $\sim$3.87), **Multi-Faceted Assessment** (mean $\sim$3.95), suggesting that progressive clues with a concrete end goal are meaningful and the assessment score sustains motivation.

Open-ended feedback underscored this positive reception. Several participants reported gaining knowledge on the sixteenth century background of Dürer's Rhinoceros and the technological importance of woodcut printing. They highlighted the enjoyment of image fusion, open campus exploration, and item creation, describing these features as conducive to both *creative experimentation* and *knowledge retention*. Improvement suggestions included faster AI model processing time and clearer tutorials. In general, these results indicate that generative AI, gamified mechanics, and an immersive Metaverse environment can effectively enhance engagement and learning for historically themed content. Lastly, **additional comments** were positive, with participants describing the experience as fun or expressing satisfaction that the system's essential features were already effective.

VIII. Discussion: Bridging Constructivist Theory and Gamified Metaverse Learning

Our pilot study supports the notion that a gamified approach to exploring historical artifacts in a Metaverse environment, augmented by generative AI, can yield greater engagement and inventive output. The findings of our pilot study underscore the ability of the MetaClues framework to integrate generative AI, gamified mechanics, and immersive Metaverse elements for creative learning in multidisciplinary contexts.

Our MetaClues-based evaluation findings further demonstrate how the MetaClues framework is built on top of seven constructivist learning goals through AI-enhanced Metaverse design, contrasting sharply with traditional classroom paradigms. This success comes from three key constructivist implementations.

1) **Student-Centered Knowledge Construction** (Goals 1,4,7): The MetaClues-based evaluation of the multi-faceted assessment mechanism (mean $\sim$3.95) and open-ended fusion mechanics allowed participants to "determine how they construct knowledge" through iterative experimentation. Unlike traditional classrooms where knowledge flows unidirectionally, $\sim$ 78.95% of users highlighted how item fusion allowed alternative solutions beyond predictable answer, exemplifying the framework's support for student-centered knowledge construction and reflection (Goals 1, 4, 7).
2) **Socially Embedded Learning** (Goal 5): The collaborative fusion stations of the virtual campus evaluated by **Constructivist learning on the virtual campus** (mean $\sim$3.89) transformed solitary textbook learning into peer-driven exploration. The emphasis of the participants on avatar and NPCs interactions contrasts with the individual work structure of traditional classrooms, with 68% reporting that item exchanges with their peers helped them "see artifacts through the perspectives of others."
3) **Multimodal Ownership** (Goals 4, 6): Cross-device workflows (mobile or desktop upload $\leftrightarrow$ desktop VR interaction) and personalized 3D inventories gave users "voice in the learning process" (Goal 4) through multiple representation modes (Goal 6). This diverges from traditional material constraints, as evidenced by MetaClues-based evaluation. Participants appreciate converting real-world photos into virtual artifacts (mean $\sim$4.00).

Taken together, these results indicate that a well-structured fusion of **gamified problem-solving** and **generative AI** can successfully spark motivation, encourage a creative thinking process and enhance domain-specific learning. The predominantly positive reception, along with practical feedback, points to a promising trajectory for future expansion. In general, the pilot study highlights the **potential of MetaClues** to function as a creative, learner-centered platform that nurtures engagement, collaboration and deeper conceptual understanding, which can be applied to diverse educational settings.

IX. Acknowledgements

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X. Conclusion

This paper introduced **MetaClues**, a novel framework that integrates **a pipeline of generative AI modules** with **gamified Metaverse interactions** to create dynamic and engaging learning experiences. By combining image-to-3D model generation, text-to-image synthesis, and a reasoning LLM-based multi-faceted scoring system, MetaClues transforms educational content into an interactive and creative journey. A preliminary user study highlights three key findings: (1) moderate to high usability (SUS) alongside strong perceived usefulness and ease of use (TAM), (2) the fusion mechanic and puzzle-like replication process boosted motivation and imaginative exploration, and (3) participants with minimal prior knowledge gained substantive insights into historical artifacts, demonstrating improved knowledge retention and educational impact.

MetaClues showcases how generative AI and Metaverse environments can simultaneously achieve constructivist learning goals through gamified design, outperforming traditional and conventional digital learning systems. Its distinct strengths lie in fostering active participation and creativity, setting it apart as an innovative educational tool.

Student feedback underscores this impact: "Campus exploration feels almost like the real thing, which is exciting," "MetaClues brings multiple users together to play and makes historical knowledge easier to grasp," and "Fusing items with AI while freely exploring the campus is really engaging." These responses highlight how an AI-driven, constructivist approach—where students actively build their own understanding—sparks genuine, self-driven interest in topics beyond their academic disciplines. By positioning learners as co-creators of their educational journey, MetaClues offers a blueprint for next-generation pedagogies tailored to the dynamic, digital-native minds it seeks to inspire.

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