Exploring the integration of metaverse technologies in engineering education through the SAMR model

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Abstract: *The integration of the SAMR model (Substitution, Augmentation, Modification, and Redefinition) into metaverse-based learning environments has the potential to enhance student engagement and outcomes by transforming conventional educational practices into immersive, interactive experiences. It provides a framework for educators to integrate technology into teaching and learning processes. In the context of the metaverse, this model can be effectively applied to create dynamic and engaging learning experiences that transcend conventional methods. The paper justifies the selection of the SAMR model to plan the integration of metaverse technologies in the presence of CAVEs, and analyses the application of the new technologies at the different stages of the SAMR model. For each stage, the paper plans the tasks for students, possible scenarios, and the role of metaverse technologies. It demonstrates the successful implementation of the model in practice and provides examples of effective practices in the context of the CAVE (Cave Automatic Virtual Environment) metaverse. The metaverse is presented as a tool to improve the learning process and to promote innovative educational approaches. The final deliverable is a plan for phased integration of metaverse learning into a Python programming course following this model, building on existing best practices.*

Keywords: SAMR, Metaverse, CAVE, Python programming.

1. Introduction

Within the broader context of the accelerating digital transformation of education, the incorporation of innovative technological solutions into learning methodologies has evolved from a mere option to a critical imperative. The integration of technologies such as virtual and augmented reality presents unparalleled prospects for enhancing teaching and learning methodologies, with the potential to substantially enrich educational experiences. However, the effective implementation of these technologies necessitates the establishment of appropriate evaluation models to assess their impact on the learning process.

The SAMR model (Substitution, Augmentation, Modification, Redefinition) offers a pragmatic framework for evaluating the depth of technology integration in education. This model, developed by Dr. Puentedura, assists educators in the effective integration of technology into their teaching practices, thereby enhancing

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educational quality (Romrell et al., 2014). As emphasised by Franco (2019), the SAMR model functions as a decision-making framework for educators adopting technology-driven instruction. The categorisation of technology use into four hierarchical levels, each representing a deeper pedagogical integration, is a key feature of the model (Romrell et al., 2014).

This paper examines the practical implementation of the SAMR model, highlighting its use in metaverse-based education, particularly within CAVE (Cave Automatic Virtual Environment) systems. It discusses the model's effectiveness in real-world educational settings and presents the metaverse as a tool for promoting innovation in teaching practices. Additionally, the paper proposes a phased integration plan for incorporating metaverse-based learning into a Python Programming course, structured according to the SAMR framework.

2. Materials and methods

This study explores the integration of metaverse technologies into engineering education, with a particular focus on their application in CAVE and Virtual Reality (VR) environments. These technologies offer innovative ways to create virtual spaces that facilitate the development of new learning scenarios and activities. The primary objective of this paper is to define the role of metaverse technologies within the SAMR model and plan their content accordingly. Under the MAGURA project, which is funding this report, we are building an immersive virtual reality laboratory based on an innovative approach for design, construction and control of the CAVE (Cave Automatic Virtual Environment). This laboratory will be a center for research, training and service, providing a controlled environment for students and faculty to conduct experiments, simulations and collaborative projects using the metaverse. High power Graphics workstation, Ultra short throw laser projectors, three wall stereo projection, Tracking system and separate interaction subsystems are used to implement this CAVE. Such a CAVE enhances functionality by providing immersive experiences, improved visual quality and optimized performance for a variety of applications on multi-user environments. Key Features of CAVE Technology are: Immersive 3D Projections; Real-Time Motion Tracking; Customizability and Interactivity; Integration of Advanced Technologies; Realism and Immersion; Dynamic Interaction; Cross-Disciplinary Use (Horan at al., 2018; Neupane et al., 2023).

The main objective of this paper is to define the role of metaverse technologies in the SAMR model and accordingly plan the content of the programming tasks through the implementation scenarios following the stages of the model.

A fundamental element of this planning process is the identification of potential learning scenarios and activities that can be incorporated into the metaverse, and the examination of how these scenarios evolve based on their level of integration within the SAMR model. The planned scenarios will be embedded into the curriculum in a manner that ensures both a robust theoretical foundation and hands-on experience through metaverse-based learning. Rather than serving merely as a substitute for conventional teaching methodologies, the metaverse is envisaged as a catalyst for innovation in engineering education, with the potential to transform how students engage with and interact with the subject matter. In the context of acquiring competence in Python programming, the Jupyter Notebook plays a fundamental role in the learning process. As a web-based interactive computing environment, it allows for the creation, execution, and visualisation of Jupyter notebooks. IPython extends the standard Python console by offering features such as autocompletion, syntax highlighting, and efficient command management, and it supports magic commands — special functions that streamline the execution of common tasks — which enhance the overall learning experience. As the core of Jupyter Notebook, IPython enables interactive code execution, fostering an engaging and dynamic approach to programming. A significant benefit of Jupyter Notebook is its portability, which allows it to be used across various devices while also enabling seamless sharing and execution of documents on different computing platforms.

“Technological pedagogical and content knowledge (TPACK) is a dynamic framework for defining teachers' knowledge. This framework is needed for designing, implementing, and evaluating curriculum and instruction with technology.” (Mishra & Koehler, 2006; Taopan et al., 2020). The TPACK and SAMR frameworks are often used when new technologies are to be implemented or the outcome of their implementation is to be evaluated. While TPACK emphasizes the integration of technological, pedagogical, and content knowledge, SAMR in higher education is particularly known for its potential to increase student engagement and learning outcomes. SAMR is a framework that provides guidance and assists educators to categorize units of study and to contextualize and select appropriate ways to apply technology in a learning context. In this report, we apply SAMR to plan the units of study for the four levels of the framework. We intend to implement SAMR together with TPACK to provide a comprehensive framework for technology integration when CAVE is built for immersive virtual reality experiments.

SAMR Model consists of four levels (Figure 1): **Substitution**: Technology serves as a direct tool substitute, with no changes in functionality; **Augmentation**: Technology acts as a direct tool substitute but includes functional improvements; **Modification**: Technology enables significant redesign of tasks; **Redefinition**: Technology allows for the creation of new tasks that were previously unimaginable.

Substitution: At this level, technology is used as a direct substitute for a traditional tool without altering the nature of the task. The primary benefit is related to increased efficiency and convenience (Hamilton, Rosenberg & Akcaoglu, 2016). For instance, using a word processor instead of manually writing notes does not alter the task itself, but it facilitates its performance.

Transition from Substitution to Augmentation: Augmentation builds on substitution by adding new functionality that was not possible with the old technology, thereby rendering the task more efficient and engaging. Collaboration tools such as Google Docs, for instance, allow students to work in real time, encouraging collaboration and communication (Mishra & Koehler, 2006).

Transition from Augmentation to Modification: Modification signifies a shift in the nature of the task itself, with the introduction of new technologies resulting in substantial enhancements. At this stage, students are no longer merely engaged in the composition of reports; rather, they are undertaking the creation of multimedia presentations that encompass text, images, video, and sound. This modification fosters creative thinking and critical analysis (Hughes, 2005).

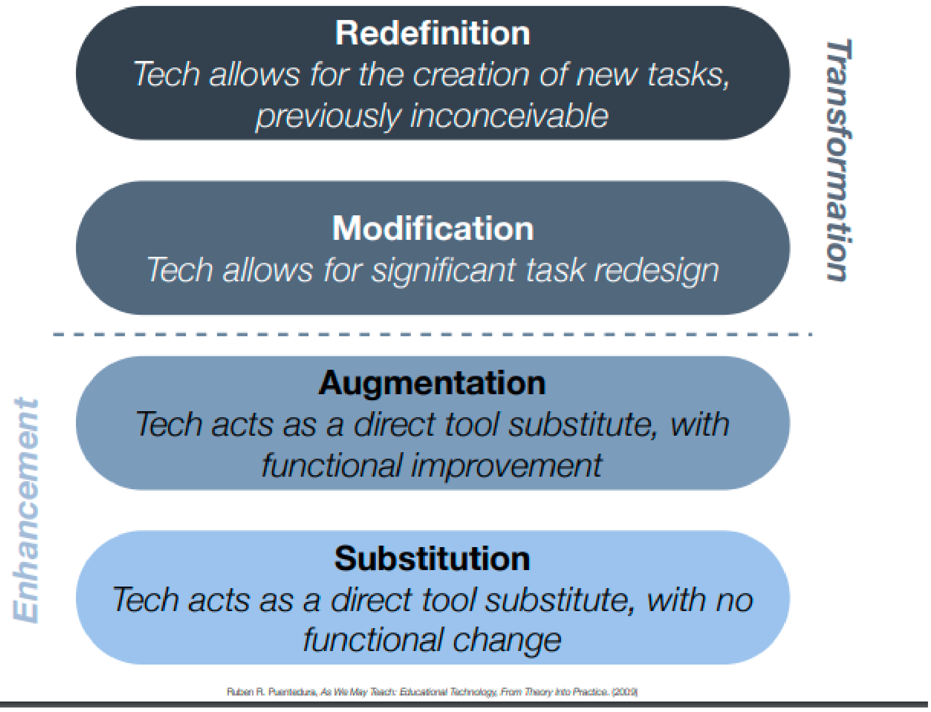

Figure 1. SAMR model (Puentedura, 2009)

Transition from Modification to Redefinition: The transformation phase represents the pinnacle of the SAMR model. This level is characterised by the ability to create tasks that were previously impossible, due to technological advancements. For instance, students can create virtual laboratories or conduct global experiments with peers from different countries through virtual reality, thereby transforming traditional education and opening up new possibilities for interactivity and collaboration (Kimmons, 2018; Puentedura, 2006).

The **SAMR model** is particularly well-suited for learning **Python programming** at the stage of integrating **CAVE and metaverse technologies** for several key reasons:

Firstly, its flexibility and adaptability. The SAMR model provides a structured framework for integrating new technologies into the learning process. Its strength lies in assessing the extent to which technology transforms education. In the context of Python programming, it enables a systematic introduction of metaverse technologies, ranging from basic substitutions of traditional methods (e.g., replacing physical classrooms with virtual environments) to the creation of entirely new learning experiences (e.g., immersive simulations where students can visualize their code in action). The model is particularly effective for disciplines that require both **practical application** and **creative problem-solving**.

Secondly, its role in aligning technology with the objectives of engineering education. The SAMR model helps evaluate the compatibility of new technologies with educational goals, ensuring their meaningful integration rather than mere adoption. In Python programming education, SAMR supports both **individual and collaborative learning** within metaverse platforms and CAVE environments. For example, in the **Modification and Redefinition** stages, students can work together in virtual laboratories, programming **interactive objects** and **real-time simulations**. This approach not only enhances engagement but also prepares students for the demands of future **industry applications**.

Thirdly, its ability to balance technological innovation with practical applicability. The model ensures that technology enhances, rather than disrupts, disciplines with **well-structured content**, such as programming. By maintaining this balance, SAMR facilitates an **effective, scalable, and future-oriented** approach to Python programming education.

3. Results and discussion

Integrating the SAMR model into metaverse-based learning environments can greatly improve student engagement and outcomes by transforming traditional educational practices into immersive and interactive experiences. In the metaverse, this model can be applied effectively to create dynamic and engaging educational experiences that surpass conventional methods. By using virtual reality and augmented reality, educators can create lessons that align with this model, transforming traditional learning into more engaging and effective experiences. This transformation fosters greater motivation and participation among students (Chen et al., 2024).

The model provides a framework for the development of technological-aided pedagogical plans, whereby the modus operandi of teaching and learning undergoes a progressive and incremental transformation. When applied to the context of teaching Python programming in a metaverse environment, this model necessitates the development of scenarios that vary in terms of technology integration levels.

In order to facilitate programming in a virtual reality based environment, it is necessary to provide appropriate code input methods. Traditional keyboards and mice can be integrated into the environment via external devices, using tracking systems for their position and interaction. Alternatively, it is possible to use virtual keyboards and gesture commands. Exploring these methods and their effectiveness is a key aspect of developing VR-based educational programming platforms.

Students can also write the code at their workstations, regardless of their physical location. All participants will be represented in the virtual environment through their avatars. They will share and discuss their programming codes in CAVE, demonstrating the achieved functionality - driving virtual cars or drones. The virtual objects will represent the results of their Python programs, and the interaction between these objects - cars or drones - will take place directly in the CAVE environment. Implementation of this functionality is planned in future developments, in view of the initial stage of research and the imminent completion of CAVE.

Regarding the implementation of metaverse-based Python learning, no preliminary results have been obtained so far. The study is still in the conceptual phase and no tests have been conducted with students or trainers.

3.1 Substitution

The metaverse can replace traditional classroom settings with virtual environments, allowing students to attend lectures and participate in discussions through avatars, as seen in the creation of a Metaverse college environment (Sineka et al., 2024). The metaverse allows students to attend classes and access resources online. This basic level of integration can help maintain continuity in education, especially in remote learning scenarios (Chen et al., 2024; Puneet et al., 2024).

At the Substitution stage, the technology functions as a direct replacement for conventional methods, exhibiting no discernible functional enhancement.

- **Introduction to Python fundamentals**: Students utilise a metaverse environment to enter code that would typically be written in a standard development environment, such as the Jupyter Notebook.

- **Scenario**: At this level, it is not necessary to work in the metaverse and CAVE. The tools we have been using so far, such as https://pythontutor.com/, are sufficient. In this environment, students can understand the code and its operation, track the execution step by step, and visualize the memory status for Frames and Objects (Figure 2.).

The other approach is in a metaverse environment. Metaverse platforms are utilized to create virtual classrooms for delivering Python programming lessons.

This approach has the potential to replace traditional physical classrooms without requiring changes to the established teaching methodology. Students can work on tasks such as writing Python code for various programming assignments. The CAVE environment enhances both the development and execution of Python scripts, providing a more immersive experience while preserving the core characteristics of the assignments.

- **The metaverse role is as follows**: The metaverse environment functions as a visual-only alternative to the conventional interface.

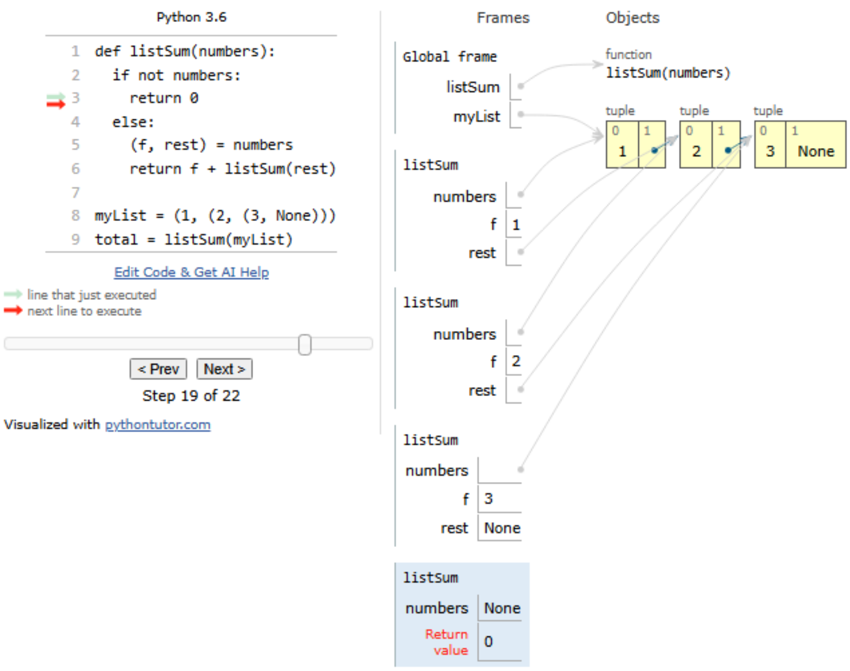

Figure 2. Python code visualization in https://pythontutor.com/

3.2 Augmentation

The use of VR glasses for attendance tracking and interactive quizzes enhances traditional educational practices by providing real-time engagement and feedback, thus augmenting the learning experience (Sineka et al., 2024). The metaverse enhances learning by incorporating multimedia elements such as 3D models and simulations, which can make abstract concepts more tangible and understandable. For instance, in STEM education, virtual labs can provide hands-on experiences that are otherwise difficult to achieve in a physical classroom (Singh et al., 2024).

The SAMR model, at the augmentation stage, has been demonstrated to facilitate functional enhancements over conventional methodologies.

- Creating visualizations with matplotlib: Specifically, students are able to develop programs that facilitate the visualisation of mathematical functions (e.g. sine and cosine) in a three-dimensional environment, thereby offering a novel and engaging way of presenting mathematical concepts.

- Scenario. At this second stage, the implementation of tasks can also be optional – in a long platform or in a metaverse environment. The integration of virtual reality or augmented reality within interactive coding environments serves to enhance traditional coding environments, thereby providing an interactive coding experience. Furthermore, the CAVE system has been shown to enhance the learning experience by providing real-time visualisation of Python program outputs. This can be particularly useful in areas such as data science or spatial analysis where visual feedback can aid understanding.

- The function of the metaverse is as follows: Visualisation in the metaverse improves concept understanding through spatial representation. Virtual reality headsets can enhance this by visualising code execution and debugging in 3D space. Tools such as IPython, an interactive Python environment, provide powerful capabilities for data analysis, code development and scientific computing. Within Jupyter Notebook, users can create and share interactive documents that integrate code, text, graphics, and other elements. This seamless integration promotes a comprehensive, cohesive approach to problem solving and knowledge representation.

3.3 Modification

The metaverse offers opportunities for significant redesign of tasks, particularly through the use of digital twins in cyber-physical systems education. This technology enables students to engage with complex systems in a virtual environment, providing a hands-on learning experience without the need for physical equipment (Yun et al., 2023). The metaverse enables collaborative projects and interactive activities that foster deeper learning. Students can work together in virtual spaces, engaging in problem-solving and critical thinking exercises that are enhanced by the immersive nature of the metaverse (Pangsapa et al., 2023; Singh et al., 2024).

The SAMR Model at the stage of Modification is planned to substantially revise the tasks.

- Programming of simulations: Specifically, students will be tasked with the creation of Python programs that facilitate interaction between objects within a metaverse environment.

- Scenario: Students are tasked with developing code to control the behavior of virtual objects. For example, a script can be designed to guide a virtual drone along a predefined trajectory. Python's suitability for interacting with objects in the metaverse environment is well established, enabling the simulation of movement and control of virtual entities. One illustrative scenario involves directing a drone along a specified route using the pynput library to facilitate keyboard interaction and movement control. Alternatively, a drone can be programmed to navigate randomly within a 3D space by leveraging the random library.

- The role of the metaverse in this context is pivotal. The metaverse evolves from a mere platform to an active component of the learning process. Students can collaborate on Python projects in real time, sharing their code and engaging with virtual objects that represent diverse coding concepts.

3.4 Redefinition

The metaverse redefines educational possibilities by creating entirely new learning experiences. For instance, the use of explainable AI within the metaverse provides personalized feedback and improves learning outcomes, as demonstrated in drone education (Yun et al., 2024). Additionally, the integration of blockchain technology for secure and open learning communities represents a fundamental shift in how educational content is delivered and managed (Rodzin et al., 2024).

The metaverse creates entirely new tasks that were previously inconceivable (e.g., virtual reality experiences) (Krisbiantoro & Ashari, 2024; Ruíz-Contreras, 2024). For example, students can participate in virtual field trips or historical reenactments, providing experiential learning opportunities that enhance engagement and motivation (Pangsapa et al., 2023; Chen et al., 2024).

At the Redefinition stage of the SAMR model, the creation of new tasks that were previously impossible is associated with the process.

- Interactive tasks adapted to the metaverse environment with CAVE: Students are tasked with the development of Python-based immersive simulations that facilitate real-time interaction between actors in disparate locations.

- Scenario: As part of the Metaverse Integration course, participants will use Python to program a traffic simulation in an urban environment, allowing interactions between objects (e.g. cars) and different scenarios. Metaverse Integration: These simulations can be extended using libraries such as the Unreal Engine Python API or Unity ML Agents to enable real-time interaction with 3D objects. The Pygame library is used to introduce the basics of simulation by visualising and processing interactions. In this environment, participants control virtual vehicles while Python-driven traffic elements dynamically respond to traffic lights, pedestrians and congestion.

Redefining learning with CAVE: CAVE enables immersive learning experiences by allowing students to develop and interact with complex 3D models and simulations beyond the capabilities of standard screens. This includes the procedural generation of structures using Python scripts that can be visualised and manipulated within the CAVE.

- The function of the Metaverse is as follows: The Metaverse functions as a medium for collaboration and innovation, significantly enhancing the learning process. At this stage of the SAMR, the development of a virtual laboratory becomes a viable proposition. Students are able to write Python scripts with the objective of manipulating virtual robots or simulating real-world scenarios. The utilisation of tools such as Blender for visualisation and Geometry Nodes for rendering can enhance the visual representation of Python-generated models.

The metaverse presents promising applications in education, especially in blended learning, language acquisition, competency-based education, and inclusive education (Zhang et al., 2022). The research highlights the importance of social interactions and flipped classroom methods in promoting engagement. It posits that integrating the SAMR model with these pedagogical approaches can potentially enhance student outcomes within metaverse environments (Pangsapa et al., 2023). Integrating the Metaverse into both STEM and HASS subjects has been shown to enhance learning outcomes through student-centered methods like problem-based learning (Mohamed, 2022).

The integration of the SAMR model within metaverse-based learning environments presents numerous advantages. Nonetheless, challenges such as the necessity for a robust technological infrastructure and comprehensive educator training must be addressed to maximize the potential of this approach. It is imperative to ensure that educators possess the requisite skills and resources to implement these technologies effectively, as this is vital for achieving the intended educational outcomes (Kurniawan & Sutabri, 2024; Chen et al., 2024). Moreover, the existing literature highlights a significant gap in the theoretical framework for creating immersive lessons in the metaverse that includes a pedagogical model (Singh et al., 2024).

4. Conclusions

The use of the SAMR model to teach Python programming in a metaverse environment involves creating scenarios that incorporate varying levels of technology integration. This paper provides illustrative examples of this application. In this study, we explicitly point to the lack of experimental validation through practical tests with students and faculty as a limitation. This will be done in our future research upon completion of CAVE.

The following ideas for future research can be successfully implemented, including integration with other technologies. The selection of platforms and the subsequent testing of their functionality and compatibility are pivotal considerations. Furthermore, it is imperative that educators are acquainted with best practices for operating within the metaverse environment and are trained to utilise novel tools and technologies, including Python programming in metaverse platforms.

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