BEYOND VR: SCALABLE 3D VISUALISATION FOR HIGHER EDUCATION

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Abstract

Interactive simulations in higher education (HE) are recognised as powerful tools for helping students understand abstract concepts. Recent advances in game engines and 3D modelling now let universities build in-house solutions tailored to their curricula. Virtual Reality (VR) offers immersive, high-fidelity visualisation but is hard to scale because of cost, accessibility, and the logistics of large numbers of headsets. Flexible, classroom-ready alternatives are therefore needed.

We launched the Synchronous Interactive Media (SIM) project to harness game engines and remote computing for cost-effective, large-scale 3D visualisations that run in standard teaching spaces without specialised VR hardware. Lecturers and students can collaborate with simulations in real time, preserving VR's interactive benefits while remaining practical.

SIM uses a pedagogy-first, interdisciplinary partnership approach: digital developers, academic staff and students co-design simulations aligned with module learning outcomes. In two complementary pilots, we developed a mathematics visualisation on conformal mapping and an earthquake-engineering simulation that lets students build virtual structures and test them under different seismic scenarios.

Crucially, technology is chosen to fit the need, not vice versa. Where high fidelity was essential, we developed a Python-to-Unreal pipeline with a pixel-streaming set-up; where a simpler approach sufficed, a Unity/WebGL app was created to run in any browser. The resulting workflow offers a flexible framework for deploying interactive educational tools across disciplines and demonstrates a scalable, cost-effective path to more accessible 3D learning experiences in HE.

Keywords: 3D visualisation, simulation, partnership, game engines, technology, higher education.

1 INTRODUCTION

1.1 Background

Extended Reality (XR), particularly Virtual Reality (VR), has become a transformative force in higher education over the past decade [1]. Advances in both delivery hardware and development software have significantly improved the quality and scalability of VR experiences.

From virtual labs to role-playing scenarios, XR's intrinsic properties enhance technology-driven teaching and learning. Numerous mature and evaluated in-curriculum interventions, alongside earlier stage pilots, demonstrate its potential [2]. On VR in particular, a growing body of literature has pointed to the technology's affordances, its immersive qualities, life-like perception of a virtual environment, interactive properties and potential for a learner's sense of both agency and presence[1].

At Imperial College London's Digital Media Lab, we have found that while these technologies offer significant benefits, many solutions do not scale to larger cohorts or varied subjects. This aligns with findings from other higher education institutions exploring effective and cost-effective scaling of XR teaching [3]. Even if cost, scheduling, space, accessibility, or maintenance barriers were somehow all removed, the pedagogical justification for wholesale replacement of traditional teaching settings with HMDs (head mounted displays) labs remains weak. That is not merely to do with modality limitations, as much as with best practice in teaching and learning and established learning design principles [4]. That is to say, learning is unlikely to be optimised by a reduction to any single modality or teaching setting, however beneficial they might prove in some scenarios.

Much of Imperial College London's on-campus teaching occurs in traditional teaching spaces, primarily raked lecture theatres. Timetabling considerations and student workload concerns also feed into

considerations around VR lab sessions and when and how those are best introduced. Consequently, XR is absent from most modules and degree courses, limiting the average student's exposure to these technologies.

1.2 Project description

Project SIM (Synchronous Interactive Media) is a cross-disciplinary initiative, funded by Imperial College London's Digital Innovation Fund [5], that aims to make high-quality, interactive, 3D simulations accessible to every student on any module. Co-led by the Digital Media Lab [6] and the Centre for Languages, Culture, and Communications [7], in collaboration with the departments of Earth Sciences and Engineering, and Mathematics, the project treats modality as flexible rather than prescriptive: instead of committing to VR alone, SIM offers a growing toolbox of scalable visualisation workflows that complement, rather than replace, bespoke XR teaching. By shifting from a *VR-or-nothing* approach to a spectrum of modalities, investment in scaled interactive learning media for teaching could become more pedagogically effective and cost-efficient.

To pilot our workflow, visualisations for two I-Explore modules [8] - one on Earthquake Engineering and one on Mathematics - were developed. These modules were chosen because they are open to students from any discipline and therefore offer fertile ground for pedagogical innovations aimed at enhancing conceptual understanding. Building on expertise from the earlier Asynchronous Interactive Media (AIM) project [9], SIM seeks to provide practicable, transferable methods for embedding interactive 3-D learning in diverse courses while staying within existing facilities, budgets and technical ecosystems.

In the Methodology section of this paper, we will discuss the overarching, collaborative development process of the project, as well as the technical specifications of each of the pilot visualisations. The Results section presents the visualisations from a user perspective, and the Conclusions discuss the principal learnings and future work.

2 METHODOLOGY

2.1 Project-wide development process

Throughout the SIM project, we adopted a methodology grounded in pedagogy, not technology. Rather than selecting a delivery modality in advance, the process began with the identification of a module that presented a conceptual or visualisation challenge in areas where traditional instructional formats struggle to convey abstract or spatially complex ideas. From this starting point, the most appropriate visualisation format was determined, considering the delivery format and intended level of interaction by both teaching staff and students. This approach ensured that all technological development served a clear instructional purpose and was embedded meaningfully within existing curricula.

Central to this methodology was a collaborative model that brought together academic staff, students, and digital developers from Imperial College London's Digital Media Lab (DML). A distinctive feature was the integration of Imperial College London's StudentShapers programme [10], which provides bursaries enabling students to act as partners in educational development projects alongside staff by contributing their learners' perspective as well as disciplinary modelling expertise. This partnership model ensured that students were not merely participants but co-creators in the development process.

The interdisciplinary teams worked closely to design, prototype, and implement interactive simulations that are student-centred and directly support defined learning outcomes. The development process was intentionally people-centred: students and staff were embedded in the iterative design of each simulation, contributing pedagogical insight as well as disciplinary skills and knowledge, which were crucial to ensure the visualisations were well aligned with the learning outcomes.

Design work was launched through a two-day, DML-facilitated design-thinking workshop. The main objective of this workshop was to introduce participants to creative approaches towards representing scientific concepts through encouraging participants to view ideas from multiple perspectives. The key outcomes were (i) agreed learning objectives for the visualisations and (ii) prototype sketches. Subsequently, students developed these into detailed designs, working with academic staff for pedagogic alignment with the modules and DML staff to ensure that visual and interactive outputs were technically feasible. The result informed the briefs for the DML team to create the final interactive visualisations for both pilots.

2.2 Pilot projects

One of SIM's goals is to create new technical solutions for 3D modelling of different types of visualisations and interactivity. We therefore purposely chose two contrasting pilot projects that would require a different technical approach. They were chosen to represent different disciplines, learning needs, and technical workflows, but both adhered to the same underlying framework of partnership-driven, pedagogy-first development.

2.2.1 Pilot 1: Earthquake engineering

This pilot focused on a multidisciplinary engineering module in which students are introduced to the fundamentals of earthquake engineering, including key concepts related to the design of seismic-resistant structures. Many of the students lack prior experience in engineering, structural analysis, and coding, or hold misconceptions about what an earthquake-resistant configuration looks like. The core pedagogical challenge therefore is enabling them to intuitively understand how different structural decisions influence a building's response to various types of seismic events. To support this, a 3D model of a realistic environment was developed to visualise the impact of recorded earthquake motions, including resulting stresses and strains on the structure.

The visualisation involved the development of a bespoke simulation pipeline combining Python-based numerical modelling with real-time 3D visualisation in Unreal Engine. An intuitive, browser-accessible 2D interface was created in Unreal to allow the user to easily assemble the building's structural configuration without the need for specialist software or high-end hardware. This 2D webapp then sends the structural and seismic parameters to a Python backend, responsible for calculating structural responses to various earthquake profiles using optimised scientific libraries.

The structural data and earthquake parameters generated through the Python engine were then passed to a pixel-streamed Unreal Engine environment. This enabled high-fidelity, interactive 3D visualisations to be launched and displayed across standard devices across campus, regardless of local computational capacity. The Unreal package incorporated a range of dynamic features, including animated structural stress responses, real-world seismic data profiles, environmental parameters, and camera control.

The Python simulation and the pixel-streaming setup used a dedicated Windows server with powerful CPUs and a physical GPU array housed within the institutional data centre, ensuring low-latency rendering and consistent performance. This infrastructure allowed the system to deliver advanced graphical and computational output comparable to local high-end workstations while remaining accessible over the existing campus network. With scalability in mind, the system was designed to be adaptable for future migration to cloud-based computer solutions.

2.2.2 Pilot 2: Mathematics

The second pilot addressed a key challenge in advanced mathematics: helping students understand how shapes are transformed by conformal mappings in the complex plane. This was one of several projects currently in the SIM pipeline for mathematics. The pedagogical aim of this pilot - as identified by the student partners - was to support students in visualising the dynamic effect of different conformal maps: how input shapes are distorted depending on the nature of the transformation. This pilot was therefore focused on the visualisation of a mathematical concept, rather than real-world structures and events as in pilot 1.

This different focus allowed for a simpler, lighter, and cheaper solution to deliver the necessary pedagogical and visualisation requirements. It provided an opportunity to leverage web-based solutions, as opposed to higher compute pixel streaming, thus piloting complementary workflows within the wider SIM project. A functional prototype of the visualisation was created by one of the student partners using the MATLAB development environment and the MATLAB App Designer. This prototype included all the functionality, but the interface was not optimised for intuitive interaction, plus accessing the prototype required software licenses and installation. As our main aim was for any student to be able to easily access all SIM visualisations, MATLAB did not fit our requirements for the final solution. The DML team therefore converted the code to C# to allow further development using the Unity game engine, which was selected for its flexibility of deployment formats. Whilst there was no intermediate bridging function between MATLAB data and Unity, a surrounding wrapper code was developed to allow the core mathematics to be controlled by User Interface (UI) elements. This User Interface was designed in Figma and implemented within the Unity engine. To ensure compatibility with lower-end computing and mobile devices, both the interface and the overall experience were optimised for performance. The simulation was compiled for WebGL to enable delivery as a browser-based application, which required additional optimisation of both the underlying code and the visual assets, such as reducing texture

quality and resolution, to ensure smooth operation on low-power devices. The WebGL code was hosted to allow client devices (such as lecterns or students' mobile devices and laptops) to access it from the web.

3 RESULTS

This section outlines the final form of each SIM pilot from the user perspective, describing how learners will interact with the simulations and how the design supports the intended learning goals. Both visualisations were designed to be introduced during a lecture session, where the lecturer demonstrates the interface and key features via the main lecture theatre display, as shown in Fig. 1.



Figure 1. A typical lecture theatre, with the lecturer demonstrating the visualisation via the main display.

Learners then access the tool on their own devices, either mobile or PC, by scanning a QR code or following a provided link as illustrated in Fig. 2.

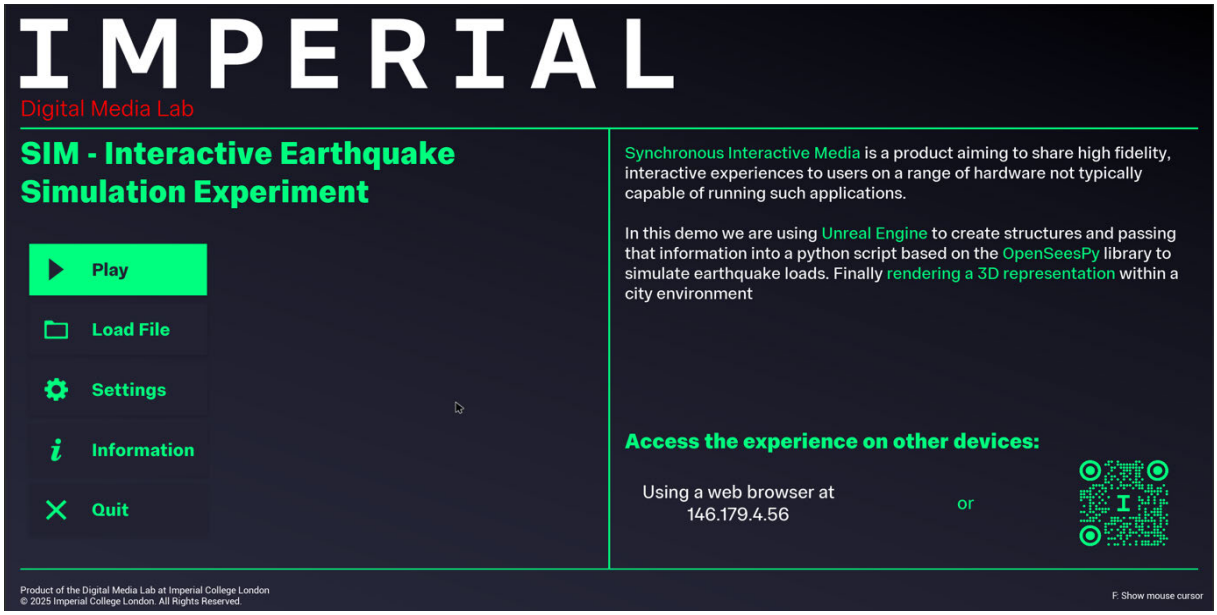


Figure 2. The screen with joining instructions: students can access the simulation via the given web address or by scanning the QR code.

3.1 Pilot 1: Earthquake engineering

Upon accessing the tool, the 2D webapp launches the ‘Builder’ interface, which can be seen in Fig. 3. Here learners can construct their own building configurations using a range of elements such as beams, slabs, and trusses, or select from a set of predefined structures.



Figure 3. A student creating a 2D structure in the ‘Builder’ interface on their mobile device.

They then select a real-world earthquake event from a curated dataset to apply to their structure and activate the simulation. This transitions the interface into a fully rendered 3D environment, which is shown in Fig. 4. In this environment, learners can manipulate contextual variables such as weather and time of day, as well as control playback of the simulation. The simulation includes real-time visual feedback on the structure’s behaviour, with key metrics, such as node-specific force data, displayed during run time.



Figure 4. The 3D environment running an earthquake simulation on the student’s structural design.

3.2 Pilot 2: Mathematics

Learners can explore a sequence of conformal mapping functions, each illustrating a specific transformation between coordinate frames. Using a set of controls, they can move basic geometric shapes (a square and a circle) across the X and Y axes and observe how these forms are distorted under different mappings. This is illustrated in Fig. 5.

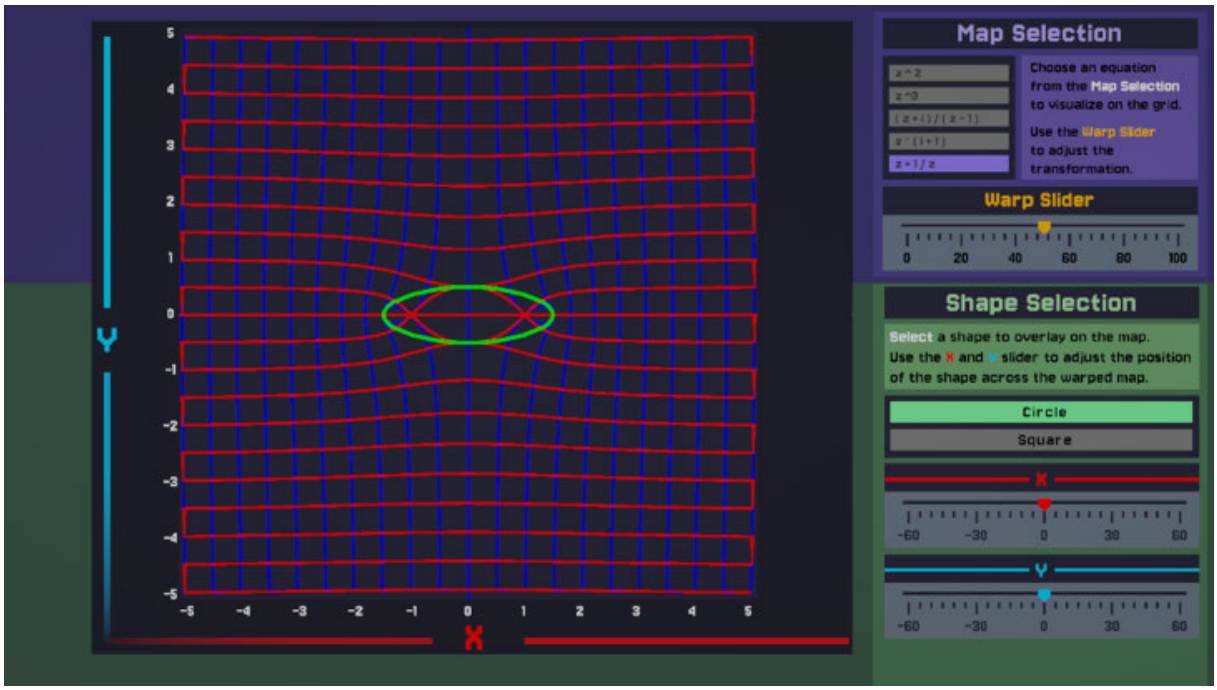


Figure 5. The WebGL User Interface illustrating the conformal mapping of a circle.

The simulation provides a visual, interactive means to understand how each mathematical function alters spatial relationships, supporting an intuitive grasp of abstract transformations. By actively manipulating the inputs and observing the outputs in real time, learners are able to build a clearer conceptual model of how conformal mappings operate.

4 CONCLUSIONS

4.1 Discussion of main outcomes

This project set out to explore how real-time, interactive visualisation can be more effectively embedded into mainstream higher education by taking a pedagogy-driven approach to design, development, and delivery mode. The main requirement underpinning any design choices was that the visualisations had to be deployed within existing teaching spaces and sessions. A key take-away is the importance of beginning with a well-defined educational challenge rather than a predetermined technology. By focusing first on what students struggle to understand, whether dynamic structural behaviour in earthquake engineering or complex transformations in mathematical mapping, visualisation choices were clearly aligned with learning objectives and easily integrated into teaching practice.

As a corollary of the pedagogy-first approach, close collaboration between academic staff, students, and the Digital Media Lab was critical to the development of tools that were both educationally meaningful and technically feasible. This led to the interdisciplinary, partnership-based model underpinning the SIM project. Through Imperial College London's StudentShapers programme, students contributed not only as learners but also as co-creators: bringing subject expertise, modelling insight, and user perspective into the development process. This approach fostered shared ownership, iterative feedback, and a culture of mutual understanding that shaped both process and output.

Several tangible innovations emerged from our collaborative process. Firstly, a replicable workflow was established in which disciplinary experts supplied models or simulations in the programming language of their choice, which were then translated into interactive 3D environments by DML developers. To this

end, a technical pipeline was developed to connect Python with Unreal Engine, allowing physics engines or mathematical processes to run in Python while being visualised in real time in Unreal. Secondly, we created an intuitive method to trigger in-class interaction with a game engine package directly from lecture slides. This was done by implementing pixel streaming from a central GPU to deliver these audio-visually-rich, high-compute, and low latency simulations to standard lecture spaces using only existing IT infrastructure. This method required minimal session-specific set-up and removed reliance on VR hardware and specialised teaching facilities. Finally, the utilisation of WebGL solutions, converting existing code to interactive in-classroom visualisation using a game engine, presents a repeatable and complementary approach that has minimal running costs and is highly applicable to many use cases.

Taken together, these outcomes demonstrate a viable pathway for embedding scalable, interactive visualisation into traditional teaching environments, one that is both cost-effective and pedagogically grounded.

4.2 Future work

At the time of publication of this paper, the two pilot projects are ready for classroom use, evaluation, and iteration. Further SIM work, including collaboration with Imperial's Chemistry department, will likely lead to new workflows, expanding the framework's possibilities. We have also begun work on adding a controllable AI back-end to the SIM workflow, coupling AI with interactive, 3D visualisations. Our aim is to explore how the resulting richer, tailored simulations can further enhance the learning experience, whilst keeping strong ethical guardrails in place.

Based on existing and future pilot studies – carefully selected to complement each other – we aim to create a set of pedagogy-led guidelines outlining which type of educational use case will be best served by which type of SIM solution, taking into account the affordances, accessibility, and intrinsic properties of the solution.

These guidelines, alongside established principles such as the DICE framework [11] for VR deployment in education, will form an interactive transmedia toolbox for educators, learning designers, and learning media producers, aiding in matching solutions with learning conditions.

Combining various interactive learning media modalities with modality-specific guidance will enable cost-effective, technologically enhanced simulation and visualisation for diverse learning context while still accommodating a wide range of practical constraints.

Because solutions from the SIM and AIM projects as well as our VR experiences all draw on the same development ecosystem - game engines, 3D modelling and UI design - the resulting delivery modalities remain scalable, adaptable and able to coexist across higher-education settings. Educators and learners will benefit from visualisations tailored to specific courses and settings, while budget holders can invest in novel visualisation and simulation technologies without over-reliance on a single setting, modality, or vendor, reducing risk and enhancing opportunity and cost-effectiveness.

While the two pilots involve some new Intellectual Property, the project intentionally uses existing, well-established development tools and workflows. This focuses resources on student-ready outcomes and facilitates knowledge sharing with other groups and institutions, driving broader aggregate change. Our long-term ambition is to contribute to a growing array of solutions that benefit learners and educators, removing barriers and sharing practices.

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