A virtual reality platform for immersive education in computer graphics

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Abstract

We present a general framework for teaching 3D imagination demanding topics using commonly available hardware for virtual reality (VR). Our software allows collaborating on 3D objects, interaction and annotation in a simple and intuitive manner. Students can follow the exposition from an arbitrary, naturally chosen point of view, and they interact with the shared scene by adding annotations and using a pointing metaphore. The software allows using various VR headsets as well as opting for a traditional 3D rendering on a 2D screen. The framework has been tested in a small course on polygon mesh processing, identifying and eliminating the most serious flaws. In its current form, most of the sources of friction have been addressed and the system can be employed in a variety of teaching scenarios.

CCS Concepts

• ***Computing methodologies*** → ***Virtual reality;*** *Mixed / augmented reality; Mesh models;*

1. Introduction

Studying computer graphics as well as many other scientific fields, such as mathematics, physics, chemistry, mechanics, etc., often leads to struggles when encountering obstacles caused by the high level of required spatial imagination and orientation in 3D space. A considerable amount of these problems stem from the fact, that in traditional teaching aids, inherently 3D concepts are explained using 2D illustrations on blackboards, in books and on slides. Many teachers resort to relying on pure imagination of the students, uttering sentences such as "now please imagine another arrow pointing straight out of the blackboard" etc., which makes grasping the concepts difficult as soon as there are multiple "imaginary" objects to keep in mind.

By using traditional methods of computer graphics, it is possible to improve the exposition by preparing 3D diagrams that can be viewed from an arbitrary point of view, using techniques of real-time rendering, but preparing such learning aids is quite time consuming. In particular, exposing a new 3D concept often boils down to guiding the students through a series of steps that build on one another. Either the instructor must prepare each step in advance, which however limits the dynamics of the exposition and prohibits reacting to the questions the students may have. Alternatively, the instructor may add new elements to the illustration manually during the presentation, however, positioning a 3D element using inherently 2D inputs is a notoriously difficult task, for which most teachers lack experience needed for a fluent exposition. Recently, with the advent of modern technologies, especially virtual reality (VR) and augmented reality (AR), the possibility of visualizing three-dimensional objects with appropriate devices, such as VR headsets, has opened up, while ensuring a sufficient degree of natural interactivity with visualized objects using various controllers and sensors connected to the VR device.

Virtual reality is a technology that enables the observer to visualize a virtual scene, most often by stereoscopic projection of an image on a headset. These devices are ideally supplemented by the possibility of interaction with the virtual world using various sensors (most often motion sensors). The first such display device was probably built by Ivan Sutherland and his student Bob Sproull [Sut68] as early as 1968, however, the greatest expansion of virtual reality technology has occurred in the last decade, when the technology became available to the general public. While the prototype VR device designed by Ivan Sutherland was so heavy that it had to be attached to the ceiling of the room, which probably also earned the designation the Sword of Damocles, today's VR headsets are lightweight devices, usually weighing no more than a few hundred grams. They attach to computers using a cable, some instead serve only as an adapter for a mobile phone, and some VR headsets are completely standalone devices that do not need to be physically connected to anything when they are used.

Headsets introduced to the market in recent months, such as the Oculus Quest 2, provide unprecedented parameters in terms of resolution (1832×1920 per eye), field of view (about 100°), refresh rates (90Hz) and available connectivity, at an affordable price (currently $299 including controllers) that allows for potentially equip-

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ping each student in a small class with her own device without the need for an excessive budget. Another advantage of these devices is the extremely low "friction", which refers to small obstacles that made using VR difficult in the past. Inside-out tracking is becoming more popular and mature, removing the need for setting up external tracking devices, and the concept of all-in-one device eliminates the need for any wires connecting the device to a computer. Essentially, with current headsets, setting up a VR session takes no more than a few seconds, making it possible to switch between VR and traditional teaching dynamically.

In this paper, we present an application intended for teaching primarily subjects in the field of computer graphics, however, it is certainly just as useful in teaching a number of other subjects. In section 2, we briefly summarize related projects for teaching with the help of VR technology. The main goal of our system is to enable the visualization of 3D models and to illustrate the algorithms discussed on them. In section 3, we describe in more detail the functions that our application offers. In section 4, we describe the architecture of our VR application and introduce the technologies on which our application is based. In section 5, we describe how the preliminary testing of the application took place while teaching the Polygonal Mesh Processing lectures, and in the end we summarize the benefits of the created application and provide possible future extensions of existing functionality in section 6.

2. Related work

Kovalčík et al. [KCBS12] introduced the VRECKO framework, which is used for prototyping and various interactive tasks in VR, which implements functions for artistic applications, such as 3D brush drawing, exploring chaotic attractors and fractals, designing mathematical sculptures and includes scene generators such as planet, city and building surfaces.

Another possibility of using VR technology in education is offered by the commercial project VR Online Classroom Template, which is available as a package for the game engine Unity software on the Unity Asset Store website. This project allows teachers and students to meet in a virtual classroom, where each participant is represented by their own avatar. The package offers user voice chat, ability to write on the whiteboard, view slides of a presentation and ability to connect using a phone instead of a VR headset.

Pena at al. presented a project called InterReality Portal [PRCGA12a] [PRCGA12c], which is an innovative mixed reality co-creative intelligent learning environment, which consists of three components. The first component is a real environment consisting of a semi-spherical sectioned screen, a camera and several sensors. The second component is the MiRTLE project environment, which is an open source toolkit for creating collaborative 3D virtual worlds. The last component is the so-called xReality objects, which is an interactive connection of real objects and virtual objects using pluggable network-aware hardware boards [PRCGA12b]. The main idea of their project is to create an Internet-of-Things-based learning environment that will allow teaching at any point of the Milgram's Virtuality Continuum [MC01]. The Virtuality Continuum is a scale used to define the variations and compositions between reality and virtuality [PRCGA12b].

One of the other solutions that offers the use of VR and AR technologies in education is ClassVR [Cla20]. It is a complete commercial solution designed for pre-school, elementary school, secondary school, higher education and even the industry sector. In addition to the application itself, ClassVR offers its own separate VR headsets, a system for their management, content for teaching and support in the installation and training of teachers.

Another related application is the Anatomyou VR [HCS20]. It is an educational mobile application that serves to present human anatomy in VR using a VR mobile phone adapter. Thanks to the application, the user can look into the circulatory, respiratory, digestive, urinary, lacrimal and female reproductive system. Additional content of this application is charged.

VR technology finds an interesting use in the creation of virtual tours of various museums, monuments, cultural events, etc. Virtual tours as such are already commonplace, for example, Google uses Street View to enable virtual city walks and viewing of world landmarks and natural monuments. Many real estate websites allow a virtual tour of the properties on offer. A number of historical monuments, as well as modern building complexes, offer the possibility of a virtual tour. Combining the principle of a virtual tour with the technology of VR headsets can offer the visitor a much more immersive and interactive experience than with a normal projection on the screen. The Augmented Representation of Cultural Objects (ARCO) [WWWC04] project, which aims at building a complete solution for creating, manipulating and managing virtual tours and presenting their content to the user, can help with the implementation of virtual tours using VR and AR technology.

3. Application requirements

In order to improve the teaching of visualization and three-dimensional imagination demanding subjects at the Faculty of Applied Sciences of the University of West Bohemia in Pilsen, we decided to create an application that allows the use of VR technology for visualization of objects and also offers several other functions that are not commonly available in teaching. This objective has been identified in the summer of 2019, before the pandemic of SARS-CoV-2, and it was mainly motivated by the favorable price and properties of the Oculus Quest headset. The bulk of development has been done by the students of a Multimedia course during the 2019/2020 academic year, and having the software ready for the Polygon Mesh Processing course in the winter semester of 2020, when teaching in person has been prohibited due to the SARS-CoV-2 pandemic, was a welcome coincidence.

The basic requirements for our application were to allow loading a 3D model from some standard file format into a shared 3D scene and to display slides of a presentation in the application, so that it is not necessary to constantly take off and put on a VR headset during a lecture. The application also offers a pointer function that allows users to point at specific objects in the scene, or parts of them, without having to represent connected users using avatars, which could make the scene confusing. It was also necessary to allow the users to draw on the surface of loaded models and paint 3D curves into space. This option can be used, for example, to show the local surface properties of a loaded 3D model. It is also possible to move and resize the displayed models in the application, with the transformation synchronized from the teacher to the students. We have targeted using off-the-shelf, cheap VR headsets, and we have focused on minimizing the friction related to using VR in a class.

A necessary condition for the possibility of using our application in teaching was to adapt the application, so that it is possible to connect to the virtual classroom without a VR headset and still use the main functionality of the application, i.e. to be able to observe the presented content. Thanks to this, students who have a problem with the use of a VR headset, e.g. students whose long-term wearing of a headset causes nausea, can also take part in the lectures.

4. Implementation

In this section, we will describe in more detail the way in which we implemented our application. In section 4.1 we briefly describe the architecture of the application, in section 4.2 we describe how data import works in our application, other functions are described in section 4.3. Section 4.4 deals with the network layer of the application, in section 4.5 we mention the hardware on which we developed and tested the application, and section 4.6 deals with the user interface.

4.1. Architecture

Our system consists of three components. The first component is a server application implemented in the Microsoft .NET environment, written in the C# language. The second component is a client for VR devices, implemented using the Unity Software game engine. The third component is a desktop client, which is also implemented using Unity Software and shares a part of the implementation with the VR client.

In fact, both client applications are implemented as a single project, which includes a platform detection mechanism, based on which the application controls are configured, so that it is not necessary to develop each client separately. In addition, the entire architecture is designed so that, if necessary, the platform can be easily expanded in the future with additional client applications, such as a web browser based client implementation.

The whole application recognizes two user roles - *teacher* and *student*. In order to log in with the teacher role, the user must know the appropriate password to connect to the room with the rights of a teacher. This password is easily configurable on the server application side. Users with the role of a student are typically denied some functions in the application, e.g. they cannot upload slides of the presentation, they cannot upload or remove the displayed 3D model, etc.

4.2. Data import

Teaching most lessons, especially in technical fields, is not possible without the projection of presentations with text and graphical content. One of the basic needs that must be met in order to be able to use a VR application without the need to frequently remove and put on the headset is the ability to project slides of the presentation directly inside the scene of the VR application.

In order to be able to display such content in the application, we must be able to convert the presentations into a format with which our application will be able to work. Most teachers use the PDF (Portable Document Format) for presentation, which has become the standard for storing various types of documents. Formats of various software for creating presentations are also widely used, such as PPT (PowerPoint Presentation) PPTX and (PowerPoint Presentation Open XML) or ODP (OpenDocument presentation), but the vast majority of these tools provide the capability of exporting a presentation to PDF.

For our application, we have created a module that allows uploading and displaying a PDF presentation with static content inside the scene. After pressing the appropriate button, the user is prompted to select the PDF presentation that she wishes to load into the application. After selecting the file, the individual pages of the presentation are converted into bitmap images and these are loaded into the application as textures. To maintain the implementation independence of the converter between the PDF and the bitmap image, the module is designed to work with any tool that allows conversion between these formats. For this reason we can easily expand the range of supported presentation formats in the future. A loaded PDF presentation is shown in Figure 1.

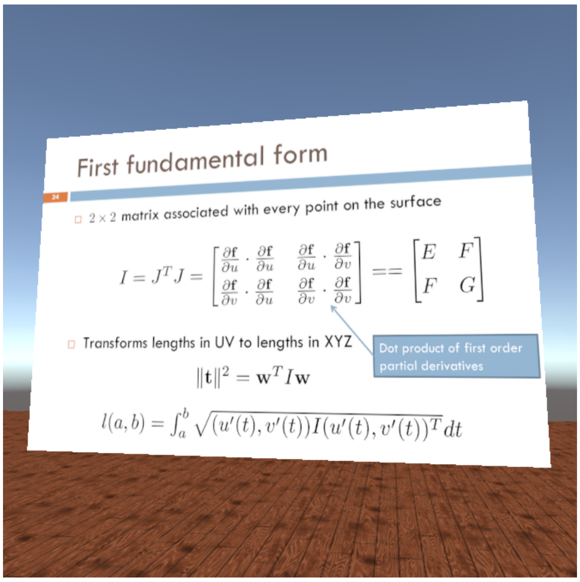

Figure 1: *Screenshot of presentation displayed in VR headset.*

To ensure the possibility of importing 3D models into our application, we implemented the loading of polygonal meshes from a Wavefront OBJ format file, which contains information about the geometry and connectivity of polygonal meshes and also allows storing texturing coordinates of the model and information about the used materials. The advantage of the Wavefront OBJ format is that most 3D modeling tools allow export to OBJ and its simplicity allows easy generation and storage of 3D models of the required properties with respect to the subject matter. The loaded model can be manipulated in the scene. In the VR client, it is possible to simply grab the object and move it, in the desktop client, the buttons for object transformation are part of the user interface.

4.3. Other functions

The application includes a function of painting into space with a 3D brush. This function can be used, for example, to annotate a loaded 3D model, to write text and equations, or to draw curves (see Figures 2 and 3). The user has the option to select this function in the VR client menu, set the line thickness and color. Subsequently, it is possible to draw and delete lines in space by moving the hand while pressing the corresponding button on the controller.

Another function that can be used to annotate objects is the ability to draw on the surface of 3D models and on the surface of the board, which is part of the scene. Here, too, the user has the option to choose the thickness and color of the line.

An important metaphore in discussing three-dimensional objects is a pointer. With the help of it, the teacher can easily point at a specific place on the surface of the model, or a student can point to a part of the scene regarding which she has a question, for example.

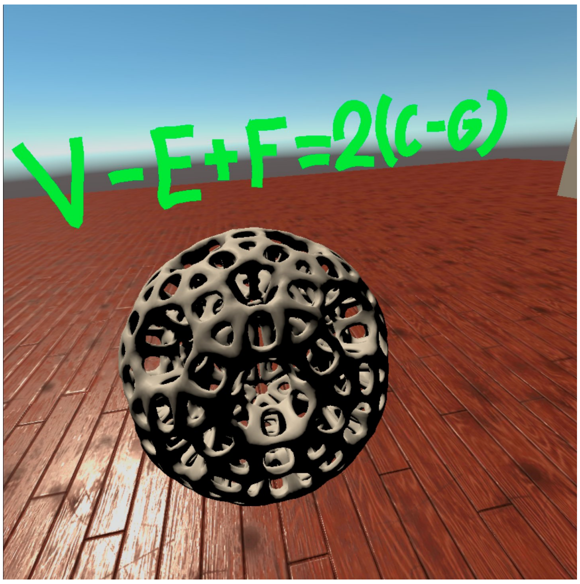

Figure 2: *Screenshot with 3D brush and loaded mesh.*

4.4. Network communication

Network communication between the server and individual clients is based on the TCP protocol and uses the KaymakNetwork library [Kay20]. The whole application uses fully centralized client-server architecture (see Figure 4), which means that there is no direct communication between clients and that the server part has all the data about the displayed scene, models, presentation and activity of other clients. In the event of an Internet connection problem at one of the clients, the quality of the presentation of other users is therefore not compromised.

All the data is synchronized between individual clients by first sending the data to the server. If necessary, they are stored on the server and then the data is distributed among other clients. Thanks to this, it is possible to ensure the possibility of reconnecting the client at any time and resending all necessary data from the server.

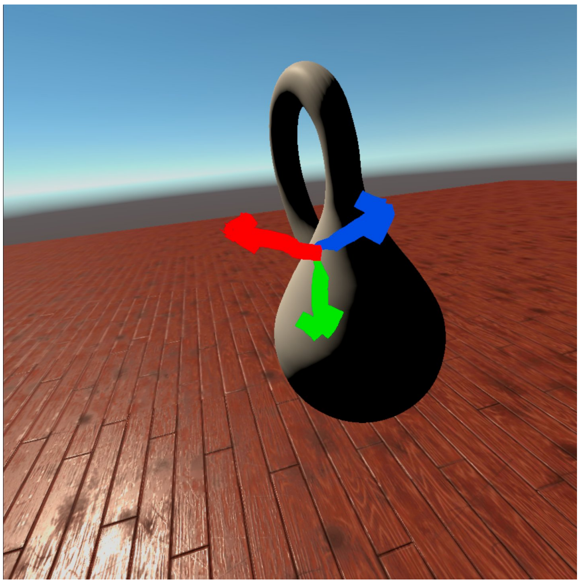

Figure 3: *Screenshot with 3D brush mesh annotation.*

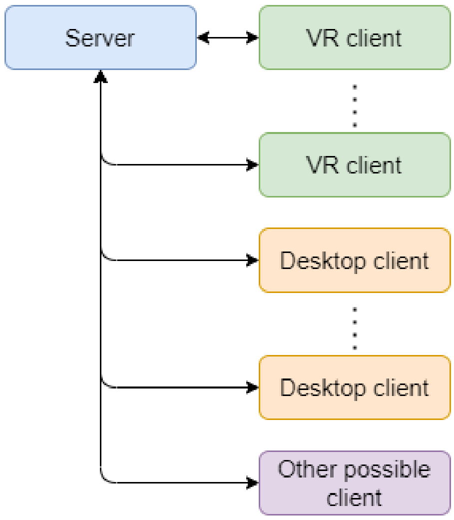

Figure 4: *Scheme of application network architecture.*

For the purpose of transmitting a larger amount of data, the network layer is supplemented by the possibility of compressing specific larger messages. This functionality is used, for example, to distribute a 3D model loaded into a scene, or to distribute the slides of the current presentation. The data is compressed using the GNU Gzip application, which is a free alternative to the standard LZW algorithm, which was patented by Unisys and IBM.

4.5. Hardware

We developed and optimized the client part of the application for VR devices Oculus Rift, Oculus Quest and Oculus Quest 2, however, thanks to the application design together with the use of Unity

Software engine, which enables publishing applications for a wide range of target platforms, it is possible to run the VR client on other platforms that allow executing VR applications.

The desktop client was developed and tested for the Windows platform, but it can also be run on the MacOS platform or on devices running the GNU/Linux operating system. The server application is currently only executable on a Windows computer.

4.6. User interface

The user interface is one of the few components that must be implemented separately for the VR client and for the desktop client, mainly due to the different way of control between these platforms. The initial screen of both clients contains fields for entering the IP address and port number of the server application, the login name and, in the case of logging in with the role of teacher, also fields for entering the password. If necessary, it is possible to configure the clients so that the IP address and port number are already pre-filled each time the application is started, which significantly speeds up students' ability to connect to a class.

After logging into the desktop client, the user is shown a control panel that contains buttons for switching between displaying 3D models and other scene content and between slides of the displayed presentation. Furthermore, the control panel contains buttons enabling the transformation of loaded models. If the user is logged in with the role of the teacher, buttons for loading a 3D model and loading a presentation from a file are also displayed here.

The user interface of the VR client available after the user logs in is designed as a menu, which is displayed in the user's hand and its position is tied to the position of the VR controller. (see Figure 5). Thanks to this location, the menu is always easily accessible to the user and she does not have to look around the scene and search for the controls. The menu offers a selection of tools, which include a 3D brush, drawing on the surface, manipulating 3D models, including resizing and selecting the parameters of these tools. Other tools are bound to specific controller buttons.

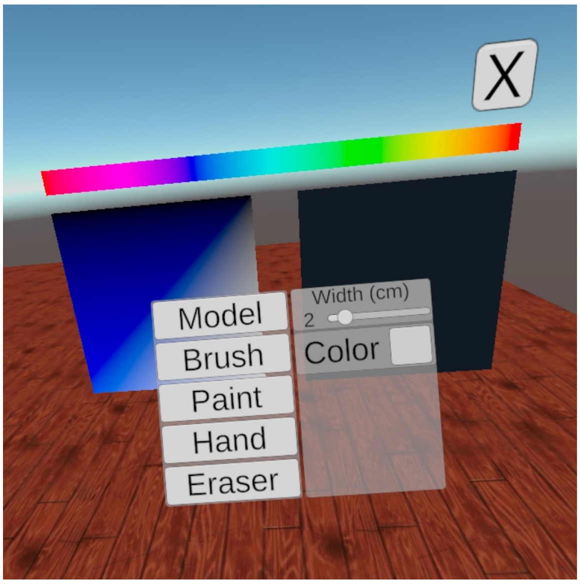

Figure 5: *Screenshot of VR tools selection menu.*

5. Testing

We tested the application during the Polygonal Mesh Processing course, which was attended by 4 students (2 female, 2 male). Two of them attended the lectures, which were using the environment of our VR learning application, mostly using a desktop client, and the other two used the VR client on an Oculus Quest device provided by the university during the lectures. Note that we had enough VR headsets available to cover all the students, the reason for picking a desktop client was merely that the students did not want to travel to the university to pick up the hardware during the lockdown.

The VR environment was used in each of the 13 lectures, however, each time only for discussing a particular 3D imagination intensive topic. Usually, the VR sessions took 10-20 minutes in each lecture. An example of a VR exposition captured from the teachers point of view is available as supplementary material of this paper. Due to the current pandemic of the SARS-CoV-2 virus, when distance learning was ordered at our university, the tool proved to be another benefit for the possibility of ensuring a sufficient quality of distance education. Since our system does not provide a voice chat, we have used a separate solution (Google Meet), which had to be employed anyway for the non-VR part of the course, and allowed voice communication during the VR sessions without serious problems. During the course of the semester, we have updated the application several times in order to address issues that appeared during the testing.

After the course, students were presented with a questionnaire in order to obtain feedback on the benefits of using our VR application in teaching. When asked whether the students find the use of our application to demonstrate the subject matter beneficial, 75% of students said that using the application was very useful and 25% of students said that the application worked well. (see figure 6).

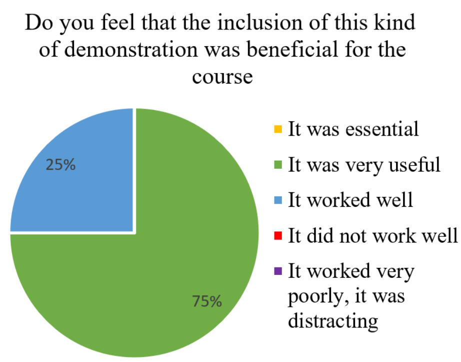

Figure 6: *Graph of the representation of answers to the question on the usefulness of the application.*

We also asked students if they would like to use this application in other courses and possibly in teaching which courses and which materials they would like to use the application. Students replied that they would welcome the use of the application in the teaching of linear algebra, mathematical analysis, machine learning and in the teaching of topology, modeling of spatial curves and plates, and possibly in the teaching of numerical methods.

According to the questionnaire, we found that the only things that bothered students when using the application were the occasional bugs and the fact that they were unable to take notes with the VR headset on. As other possible functions that would be welcome in the application, students mentioned the possibility of saving the scene for further studying the subject, better manipulation with 3D models and the possibility of automatic recording of sessions.

Overall, the students evaluated the use of the application in teaching the course Polygonal Mesh Processing very positively. They indicated that the application often made it easier for them to understand the problems, and welcomed the opportunity to view the displayed scene from multiple perspectives. The application helped them mainly in understanding differential geometry, curvatures, tangent vectors and normal vectors. Complete results of the questionnaire are available as supplement of this paper.

6. Conclusion

In this article, we introduced a new application for teaching using virtual reality. The application allows the display of three-dimensional objects, their manipulation and their annotation using implemented functions such as drawing a 3D line with a brush and drawing on the surface of three-dimensional objects. The application also allows displaying the content of presentations. A desktop client was created for the application, which allows access to teaching even without a VR headset. Thanks to its network layer, the application can be used not only for teaching in one room, but also for distance learning, which proved to be very useful while contact teaching was banned during the SARS-CoV-2 pandemic.

In contrast with many similar attempts, our software does not attempt to imitate in-class experience, but since it was primarily meant as a teaching aid rather than class replacement, it focuses on exploiting the inherent properties of the shared virtual environment. The ability to walk through objects or multiple users being located at the same position in space are not avoided, but embraced. The application was tested in the Polygonal Mesh Processing course at the University of West Bohemia and, according to student feedback, proved to be a very useful tool enabling easier insight into a number of discussed issues.

In future work, we would like to expand the application with a number of other functions, such as support for other formats when loading presentations and three-dimensional models, such as STL (StereoLithography), FBX (Filmbox), 3DS (Autodesk 3D studio). We would like to add the possibility of recording a session, saving scenes, voice chat, etc.

The use of the application in teaching clearly showed us that virtual reality technology, or possibly augmented reality, can be a useful aid in the education of STEM subjects in particular, as it can streamline the learning process and help students orient themselves in the problems associated with three-dimensional space. Current hardware provides sufficient quality and low enough friction for a fully practical application. The source code of our system is available at https://gitlab.kiv.zcu.cz/vrclassroom/public, free of charge for educational purposes, and we hope that it will help others to improve their teaching methods.

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