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Application of Virtual Reality in Learning Quantum Mechanics

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Abstract: Quantum mechanics is a physical theory that describes the behavior of microscopic matter. According to quantum theory, a microscopic particle may be described as either a particle or a wave, called wave–particle duality. Many students in high school or college (BC level) find it difficult to imagine that microscopic particles have both particle and wave properties. This is mainly caused by the scale of the world they see since quantum mechanics deals with things that are too small, while the wave and particle phenomena at the microscopic scale are difficult to understand, measure, or verify in the real world. In this study, virtual reality technology was used to develop teaching modules on quantum mechanics, allowing learners to see the particles and wave phenomena of electrons and photons in the microscopic world through interactive operation in virtual experiments. A teaching experiment was conducted by recruiting 60 high school students as research subjects. The control group (30 students) used physics textbooks, and the experimental group (30 students) used the virtual teaching modules for learning quantum mechanics. The analysis results show that the experimental group's learning effectiveness is higher than the control group. The questionnaire results show that students were satisfied with the learning experience using virtual teaching modules with high learning motivation and low cognitive load because virtual reality can visualize the abstract concepts of wave–particle duality and help them understand quantum mechanics.

Keywords: virtual reality; quantum mechanics; wave–particle duality; learning effectiveness; learning motivation; cognitive load; system satisfaction

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1. Introduction

Quantum mechanics is a physical theory that describes the behavior of microscopic matter [1], and it is essential for understanding all fundamental forces other than gravity. Its appearance has caused revolutionary changes in physics, so quantum mechanics and relativity are considered the two pillars of modern physics. In 1687, Isaac Newton, a famous physicist, mathematician, and astronomer, used induction and deduction to explain the physical and mechanical principles of the conservation of momentum and angular momentum. The three laws of motion and the law of universal gravitation laid the foundation for classical physics and established a firm foundation [2].

Before the emergence of quantum theory, it was generally believed that Newtonian mechanics was sufficient to explain the motion of all objects. With the continuous improvement in science and technology, physicists have gradually discovered that although the theory of classical mechanics can accurately describe the motion of objects, it must meet two prerequisites: the size of the object is much larger than atoms, and the speed of the object is much less than the light speed. When humans begin to explore the microscopic world, the properties of matter automatically exhibit quantum effects, and the wisdom of classical physics was unable to explain many physical phenomena. In order to solve these problems, quantum mechanics and relativity were developed in the early 20th century and greatly changed our understanding of nature [3].

In 1900, German physicist Max Planck introduced the concept of energy quanta to overcome the difficulty in classical physics in explaining the law of black body radiation, which laid the foundation for quantum theory [4]. After that, Albert Einstein analyzed the photoelectric effect and proposed the light quantum hypothesis in 1905 [5]. He believed that electromagnetic radiation is composed of photons discretely distributed in space and thus solved the problem of having difficulty explaining optical phenomena with the classical theory of electromagnetic waves. In 1913, Bohr successfully explained the spectrum of hydrogen atoms by using the concept of quantization based on Rutherford's nuclear model [6]. In Bohr's hydrogen atom model, electrons move as standing waves, and the length of their orbits must be an integer multiple of the wavelength to form a stable standing wave around the nucleus. The period from 1900 to 1913 can be called the initial stage in the development of quantum theory.

Over the next few years, many physicists worked hard to develop quantum theory but encountered great difficulties. In order to solve these fundamental problems, they could only wait for the emergence of a new idea, that is wave–particle duality. According to quantum theory, every quantum entity may be described as a wave or a particle. Einstein proposed this property in 1905 and 1916 [7], and it was verified by the photoelectric effect experiment of Millikan and the X-ray scattering experiment of Compton, but the matter wave theory was not confirmed until it was proposed by de Broglie in 1923 [8]. In the following years, scientists' findings such as Heisenberg's uncertainty principle, Schrödinger's wave equation, and Born's wave function by probability [9] finally formed a complete theory of quantum mechanics, and all together with Einstein's theory of relativity became the two theoretical foundations of modern physics [10].

In 1928, Dirac applied the theory of relativity to quantum mechanics with the contribution of Heisenberg, Pauli, and other scientists. After that, quantum electrodynamics was thus formed as the basis to develop the quantum field theory of electrodynamics based on relativity. It studies the interaction between electromagnetic fields and charged particles and is mainly used to explain the phenomena caused by the interaction of all charged particles through the exchange of photons [11].

Quantum mechanics is the basic theory used to describe the physical properties of nature in the microscopic world. It is effective in explaining atomic structure, properties of chemical elements, the regularity of atomic spectrum, absorption and radiation of light, and other phenomena. Its development extends to many high-tech fields, such as quantum physics, quantum optics, quantum chemistry, quantum computing, superconducting magnets, etc. A quantum computer is a physical instrument that performs high-speed mathematical and logical operations by following the laws of quantum mechanics. It can use properties such as quantum superposition and quantum entanglement to process more complex information [12]. Quantum computers have fast computing speeds compared with ordinary computers, and they can crack the existing public key cryptosystem within a few seconds. Due to the widespread application of quantum theory, researchers in different fields, such as physics, chemistry, optics, electrical machinery, and information technology, must have a basic understanding of quantum theory.

It is difficult for many people to understand that microscopic matter has both particle and wave properties because of the scale they see in the world. Quantum mechanics deals with wave and particle phenomena on the microscopic scale, which is too small and thus difficult to understand, measure, and verify. American physicist Feynman [13] once said: "I think I can safely say that no one understands quantum mechanics." Many high school physics teachers believe that students find quantum theory difficult because it goes against human intuition. They can use intuition in many fields but cannot explain quantum mechanics with common thinking patterns because this intuition is invalid. In addition, quantum mechanics combines advanced mathematics and statistics. In order to help them understand the basic theories and important concepts in quantum mechanics, this study applied virtual reality technology to design the teaching modules of quantum mechanics for learners to see the particles and wave phenomena of electrons and photons in the virtual world and the uncertainty of their positions and momentum through interactive operation, helpful to understanding quantum mechanics.

Virtual reality allows people to enter a virtual situation created through 3D visual effects, and it uses human senses and immersive equipment to simulate things in real life. In the virtual world, users can see, hear, or touch virtual objects as if situated in the real world, and they can also interact with others in real-time [14,15]. When the user's position changes, the computer can perform complicated computations immediately and return accurate simulated visual images to produce a feeling of presence. Virtual reality integrates technologies such as computer graphics, artificial intelligence, simulation, sensing, display, and network parallel processing. It is a real-time simulation system developed by modern information and communication technologies [16]. Virtual reality has been applied in engineering, science, education, entertainment, and national defense because a virtual environment can avoid the danger and cost incurred in real environments while achieving realistic sensory effects [17].

Dalgarno and Hedberg [18] believed that virtual reality has three elements: it has a three-dimensional visual effect that can simulate the real world; it can help build personal knowledge; it allows learners to move freely in different sizes or viewing angles to manipulate things in the virtual world with a higher degree of awareness and understanding of the created situations. Burdea and Coiffet [19] believed that virtual reality is a real-time interactive system connected by computers and peripheral devices with the features of immersion, interaction, and imagination. Virtual reality is simulated through our sensory organs to provide situations that are difficult to achieve in the real world. Users can interact with virtual things in the virtual space in real-time, so it is very suitable for applications in science education. Virtual reality is able to simulate our real world with 3D visualization to demonstrate principles, abstract concepts, and experimental processes in a realistic way, which can provide students with a learning situation close to the real world such that they can obtain exemplary knowledge and help them understand the internal meaning of these concepts or principles.

Many scholars have been engaged in research combining virtual reality and educational issues. Resnick and Morgan [20] pointed out that some universities hope to develop new learning environments, allowing students to experience the operation process without danger or risk (for example, anatomy or dangerous chemistry experiments), and virtual reality can solve such problems because students can manipulate things in the virtual environment, thus supporting the "learning by doing" and "active inquiry" environments required in science education [21]. In the traditional teaching model, learners obtain knowledge passively in the classroom, so it is difficult to experience real situations. Virtual reality allows learners to manipulate objects as they would in the real world, which is a more effective way to attain knowledge and develop concepts through active participation and interactive exploration [22].

In the research field of science education, there are many natural phenomena that cannot be presented in their original appearance, so science teachers often use computer animation to simulate these phenomena. Although learners can see the visual effects, they cannot internalize into their cognitive structure through the migration process. If the virtual environment is used to enable learners to manipulate the variables in the simulated situation and observe the results, it can modify their behavior and way of thinking to figure out a method for solving the problem [23]. This is a learning method that transforms abstract knowledge into concrete experience, which can make up for the deficiency of applying what they have learned in the traditional teaching methods. Taking this research as an example, if learners can observe the wave phenomena of electrons and photons through performing virtual experiments, it is helpful for understanding the concept of wave–particle duality in quantum mechanics.

The theory of situated learning [24] states that learners can acquire knowledge in a real or virtual situation by interacting with people and things through active participation. The main goal of situated learning is to help learners find solutions to problems through observation, participation, and discovery. Brown, Collins and Duguid [25] argued that knowledge is a partial product of the context, activity, and culture and is situated in the environment where it is developed and used. They proposed teaching strategies such as authenticity, interweaving, connection, reflection, circulation, and multimedia to enable learners to gain knowledge and experience from the interactive process. This study used the interactive and situated learning environment created by virtual reality technology to allow learners to conduct quantum mechanics experiments, enabling them to gain knowledge and experience from the operation process.

Cognitive load theory was proposed by Sweller [26], and he considered that the quality of an instructional design would generally result in significant effects on the cognitive load of a learner. Cognitive load depends on the amount of information that "working memory" can hold at one time. Because the capacity of working memory is limited, the instructional design should not use additional activities that are not directly contributive to learning because of overloading. A description of the instructional design principles generated by cognitive load theory can be found in [27], where the experiments providing evidence for the effectiveness of the principles are considered.

Cognitive load theory indicates that before the new knowledge schema of the learner is formed, there are three types of cognitive load generated in the working memory, namely, intrinsic cognitive load, extraneous cognitive load, and germane cognitive load. The correlation between cognitive load theory and schema is that schema plays an important role in learning and memory, while cognitive load theory explores how learners deal with the mental resources needed for various complex tasks. The basic assumptions related to the schema in cognitive load theory can be found in [28].

Quantum mechanics is an important foundation of modern physics. At present, there are few studies using virtual reality for teaching quantum mechanics, and few empirical studies have been conducted to explore its learning effectiveness. Therefore, this study used virtual reality to develop the teaching modules of quantum mechanics suitable for university and high school physics courses, and the objective is to provide a scaffold for self-learning to promote conceptual change by making the abstract and complex concepts of wave–particle duality more concrete and observable.

This study aims at the popularization of science education through promotional activities. Learners can wear a head-mounted display (HMD) for immersive learning or use a mobile device such as a tablet computer to facilitate independent learning, which is of great help to physics teaching in high schools and colleges. Learners may find that understanding quantum mechanics is not very difficult, and they would like to learn and have the ability to apply new knowledge in solving problems. According to the above research goals, there are four research questions in this study:

- What is the impact of virtual reality on the learning outcome of quantum mechanics?
- What is the impact of virtual reality on the learning motivation of quantum mechanics?
- What is the impact of virtual reality on the cognitive load of quantum mechanics?
- What is the system satisfaction of learners after using the virtual teaching modules?

The rest of the study is organized as follows. Section 2 describes the virtual teaching modules developed in this study and their design principles and operation procedures. Section 3 describes the teaching experiment and the analysis result. Section 4 provides the discussion and findings of this study. Section 5 is the conclusion and future suggestions.

2. Virtual Teaching Modules

In this study, virtual reality technology is used to develop the teaching modules of quantum mechanics, which embody and visualize the wave–particle duality of microscopic matter for learners to see the particles and wave phenomena of electrons and photons by conducting virtual experiments to understand quantum theory. This study analyzed the learning content according to the "Curriculum Guidelines of 12-year Basic Education" proposed by the Ministry of Education, Taiwan [29] and the textbooks of quantum phenomena in the field of natural sciences in senior high schools, and designed the learning objectives and virtual teaching modules based on the analysis results.

After completing the virtual teaching modules, this study conducted a teaching experiment to explore the learning effectiveness, learning motivation, and cognitive load of applying virtual reality in learning quantum mechanics as well as learners' satisfaction with the teaching modules, which can be revised according to the questionnaire results and suggestions from teachers to facilitate the subsequent promotion activities. The research method and steps adopted in this study are shown in Figure 1.

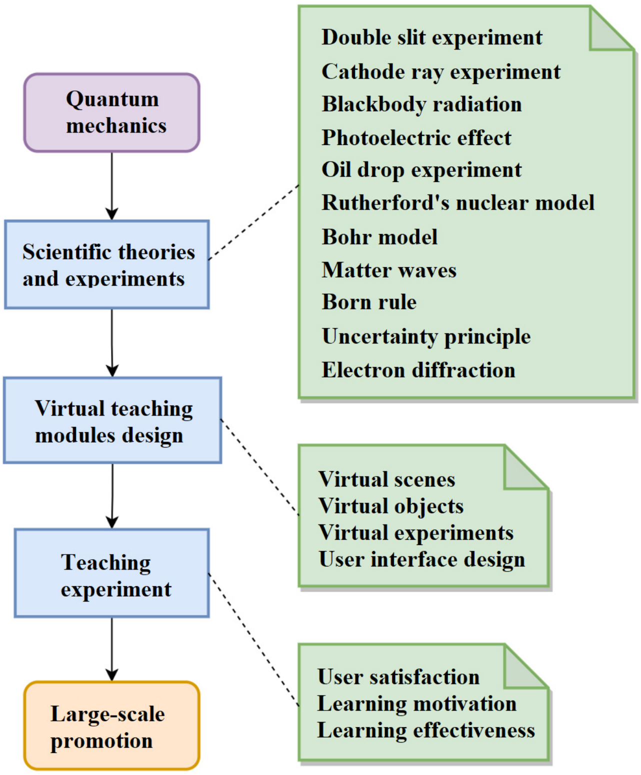

Figure 1. The research method and steps adopted in this study.

The virtual teaching modules developed in this study combined the situated learning theory and the knowledge of quantum mechanics by integrating the particles and wave phenomena of electrons and photons into observation activities, allowing learners to understand quantum theory by conducting virtual experiments. The goal is to enhance their learning motivation and understanding of quantum theory.

This study analyzed the course content first and then planned and designed teaching modules based on the teaching objectives. The designers used the Windows 10 operating system and Unity 3D Game Engine as development tools. The latter has a cross-platform function, which can develop and execute stand-alone games on PC or Mac OS. It can also support multiplayer online games. This study used Adobe Photoshop to draw the textures required for virtual objects and virtual scenes and built 3D models with Autodesk 3D Studio Max. After completion, the models were exported to Unity 3D, and then JavaScript and C# were used to write programming languages to design interactive user interfaces for the quantum mechanics virtual experiments.

Unity 3D provides a hierarchical environment and a visual editing interface for designers, including the property editor and the dynamic preview function. It is a popular development tool for building cross-platform 2D and 3D games and interactive environments. In this study, Unity 3D is used to import all objects in the teaching modules into the virtual experiments. The visual effect was enhanced through the built-in API and light source projection settings, and then the user interface was designed according to the operation process of the virtual experiment, which was published through Unity 3D. Finally, the project was converted into an executable file in the Android environment, including the HMD and mobile devices (tablets and smartphones).

This study referred to the quantum mechanics textbooks in high schools and colleges for developing virtual teaching modules. Before designing the 3D models of the experimental equipment, the size and resolution of the models must be determined. Then, 3ds Max was used to edit the model designed by hand or scanned by a 3D imaging system. Textures and light sources were set to increase the sense of reality. In order to maintain execution efficiency when performing the virtual experiment, a low-polygon design method was adopted in this study to save storage space and calculation time required in real-time simulation. In the following, the (1) Cathode-ray tube experiment, (2) Oil drop experiment, (3) Photoelectric effect experiment, (4) Gold foil experiment, and (5) Electron diffraction experiment are shown as examples to illustrate the design principles and operation procedures of these virtual teaching modules.

2.1. Cathode-Ray Tube Experiment

A cathode-ray tube is a vacuum glass enclosure containing an electron gun, an electron source, and a fluorescent wall. The electrons can be accelerated and redirected by an internal or external voltage. When the electrons hit the fluorescent wall, a light spot is generated. Electrons are accelerated by an electric field in the cathode-ray tube from one end to the other. When the electrons hit the fluorescent wall, the kinetic energy is converted into heat and X-rays. This study used 3ds Max to build the 3D model of the cathode-ray tube and then used C# in Unity 3D to design the user-interface programs for changing the voltage of the electric field to control the deflection of electrons.

When using the virtual teaching module, the user first removes the gas in the cathode ray tube to reduce the pressure, and connects two metal pieces with high voltage to ionize the air and make it an electrical conductor, and then connects the metal pieces at both ends of the glass tube to an external voltage to accelerate electrons from one end to the other. After the cathode is heated, the electrons released by the electric field quickly move to the positive electrode. The electrons passing through the anode will hit the phosphorescent material on the tube wall to generate a light spot. In order to identify the passage of the electron beam, the user can install the positive and negative electrodes of the electric field on the lower and upper sides of the cathode ray tube separately and apply a voltage for deflecting the electrons. The electron beam will be repelled by the negative electrode and deflected to the positive electrode. The user can observe how the fluorescent light is deflected downward to understand that the particles of the cathode-ray tube are negatively charged (Figure 2). A magnetic field can also be used to balance the force on the electrons for the calculation of its mass-to-charge ratio.

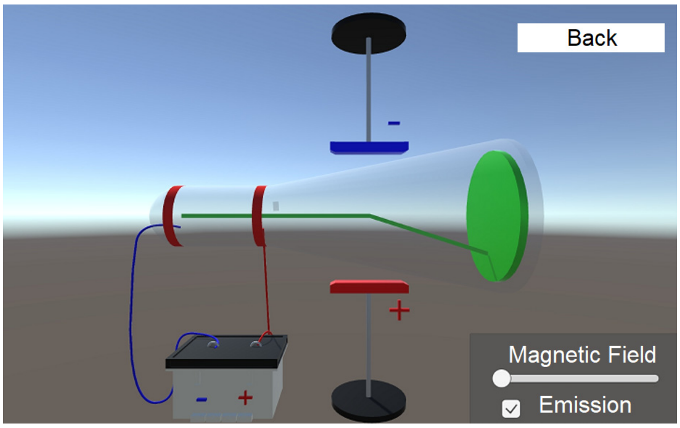

Figure 2. Virtual cathode-ray tube experiment.

If the learner applies a magnetic field B in the direction perpendicular to the electric field of the cathode-ray tube, the electrons will move in a circular motion under the action of the magnetic field when the electric field stops acting as described below, according to Newton's second law of motion.

$$F = qvB = ma_r = \frac{mv^2}{r} \tag{1}$$

In the above formula, the radius of the circular motion of the electron can be calculated as

$$r = \frac{mv}{qB} \tag{2}$$

If the magnetic field B and electric field E are adjusted so that the electrons are not deflected, it means the magnetic force is equal to the electric force, i.e.,

$$F_B = qvB = F_E = qE \tag{3}$$

After eliminating the charge q in the above equations, the velocity of the electron can be calculated as

$$v = \frac{E}{B} \tag{4}$$

By balancing the magnetic force and electric force, we can calculate the velocity v of the electron and then use the equation of the circular motion to find the mass-to-charge ratio of the electron using the following equation

$$\frac{q}{m} = \frac{v}{rB} \tag{5}$$

In this study, the virtual experiment allows learners to ionize the air using a high voltage to make it an electrical conductor and adjust the electric and magnetic fields to balance the force on the electron so that it will not be deflected, and then calculate the mass-to-charge ratio of the electron according to the above formula. They can continue with the oil drop experiment to calculate the charge and mass of electrons.

2.2. Oil Drop Experiment

The oil drop experiment contains a pair of parallel metal plates in the observation chamber and an oil sprayer to produce oil drops between them because water drops are easy to volatilize under the light source. Learners can observe through the microscope that the fine mist of oil is sprayed into the space above the metal plate, and there is light shining between the metal plates for observing the oil drops. When the oil is sprayed, it will rub against the nozzle to generate electric charges. The upper metal plate has a small hole, and the oil drops will pass through it due to gravity (Figure 3).

The learner can conduct a long-term observation. When the oil drop falls at a constant speed, the gravitational force and the electric field force on the oil drop are equal, i.e.,

$$m_{\mathrm{drop}}g = q_{\mathrm{drop}}E \tag{6}$$

The oil drop is charged by gaining electrons, and its mass can be obtained by measuring the diameter and density. The total electricity of the whole oil drop can be calculated based on the known strength of the electric field as

$$q_{\mathrm{drop}} = \frac{m_{\mathrm{drop}}g}{E} \tag{7}$$

Millikan devised an ingenious method to calculate the size of the oil drop, which would fall at a constant speed under air resistance, with the final speed depending on its radius and the viscosity of the air. He used the known viscosity of the air to calculate the radius, mass, and charge of an oil drop. After repeating hundreds of experiments, Millikan found that the total charge of all oil drops is a multiple of the same number. He used the greatest common factor to obtain the value and determined that this value is the basic charge carried by an electron, i.e., 1.6×10^{-19} Coulomb.

The virtual experiment designed in this study allows learners to adjust the strength of the electric field to make some oil drops remain still and then calculate the charge amount of different oil drops according to the strength of the electric field and the diameter of an oil drop, and finally obtain the greatest common factor of the charge amount for all oil drops, which is equal to the elementary charge of an electron.

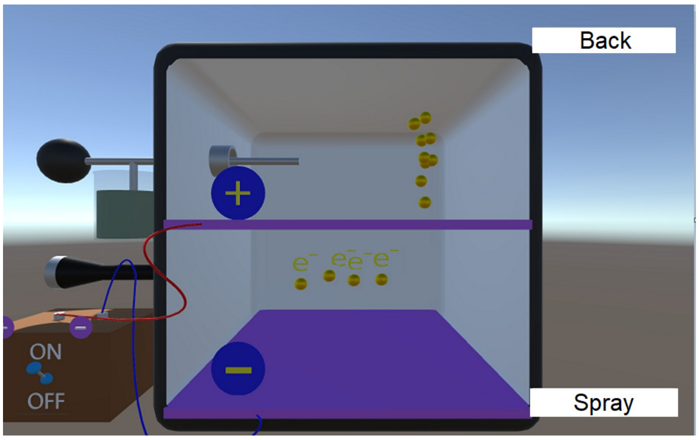

Figure 3. Virtual oil drop experiment.

2.3. Photoelectric Effect Experiment

The black body radiation experiment started the study of quantum effects, and then scientists established the foundation of quantum mechanics through several well-known experiments. Among them, the photoelectric effect experiment is the most famous experiment of light quantization, and it is also an important basis for understanding modern physics. A photon with an energy higher than the binding energy of a metal has the opportunity to eject electrons from a metal surface, thereby generating photocurrent, which cannot be explained by classical electromagnetic theory. According to Planck's formula, if the frequency of a photon is ν, then its energy is $E = h\nu$. When a photon hits a metal, if the electron is to be ejected from the metal surface, the binding energy of the metal surface must be overcome for the electron to escape; if there is any excess energy, it will be converted into the kinetic energy of the electron.

The phototube structure of the virtual photoelectric effect experiment is shown in Figure 4. The electrode that irradiates the light source is called the emitter, where electrons come out. Connecting the cathode of the DC power supply to the emitter and the anode of the DC power supply to another electrode, the electrons will move to the positive electrode to form a photocurrent, so the positive electrode is called a collector. Reversing the voltage between the emitter and the collector of the photocell results in a retarding voltage. If the potential difference between the two electrodes by the retarding voltage is greater than the maximum kinetic energy of the electrons, they are not able to reach the collector, and the photocurrent will become zero. The applied retarding voltage is called the stopping potential, which also depends on the material of the metal surface.

From the experimental results of the photoelectric effect, it can be found that the photon energy $h\nu$, binding energy φ, and the deceleration potential energy eV have the following relationship: $eVh = -\nu\varphi$, where e is the electron charge, V is the deceleration voltage, ν is the frequency of incident light, h is Planck's constant, and the binding energy φ will vary with different metals.

The virtual experiment of the photoelectric effect designed in this study allows learners to change the frequency of incident light and intensity of the photocell and adjust the deceleration voltage to observe the current change. Learners can determine the metal in the photocell from the binding energy measured in the experiment and understand that the frequency of light must be higher than the cut-off frequency of the phototube to produce the photoelectric effect, regardless of the intensity of the light source.

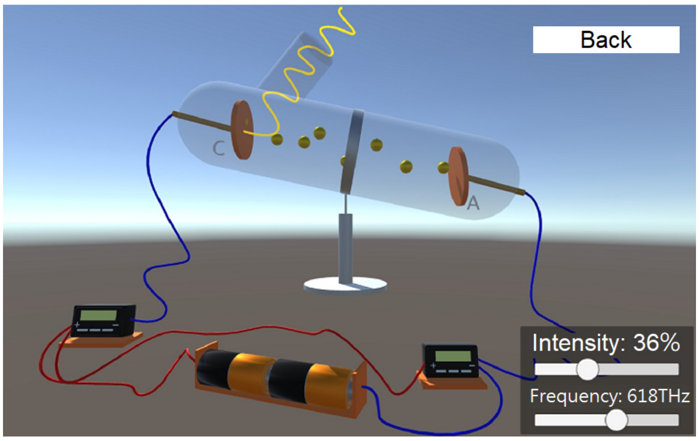

Figure 4. Virtual photoelectric effect experiment.

2.4. Gold Foil Experiment

The nuclear atomic model is an important theoretical model of atomic structure, and it was proposed in 1911 by Ernest Rutherford [30], a New Zealand-born physicist. The formation of this model had a profound impact on our understanding of atomic structure, and it led to the later development of quantum mechanics. In this model, an atom is depicted as an extremely small, dense core in which positively charged protons are concentrated in the center of the core, surrounded by a light cloud of electrons.

The model was proposed based on the famous gold foil experiment performed by Rutherford in 1909. In this experiment, Rutherford and his colleagues emitted a beam of α particles, helium nuclei containing two protons and two neutrons, at an extremely thin gold foil. They observed that most α particles passed through the gold foil unimpeded, but some were scattered when impacting the gold foil. This experimental result violated the common atomic model at that time, i.e., the "plum pudding model" composed of positrons and negative electrons with uniform mass distribution.

The virtual gold foil experiment designed in this study allows learners to emit α particles from the lead block by clicking the eject button (Figure 5) and observe that the electrons passing through the gold foil will produce flash points on the surrounding fluorescent screen. In addition, the learner can also switch the viewing angle to observe the scattering of α particles as they approach gold atoms.

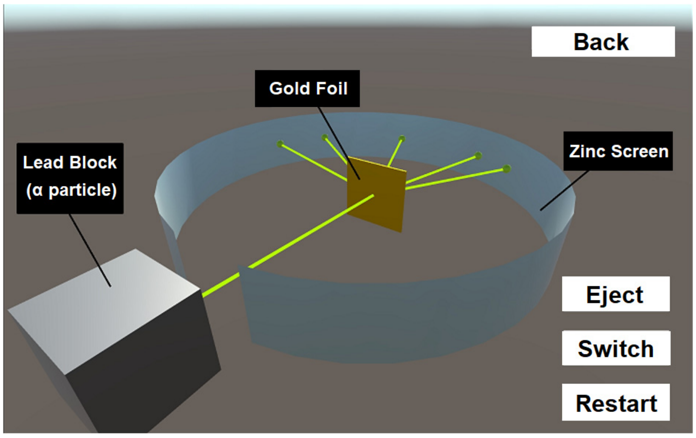

Figure 5. Virtual gold foil experiment.

2.5. Electron Diffraction Experiment

An electron diffraction experiment is a classical physics experiment used to study the wave properties of electrons or other small particles. This experiment is intended to confirm the wave–particle duality of matter proposed by de Broglie. In the electron diffraction experiment, a beam of high-speed electrons is directed through a thin layer of metal, e.g., gold foil, to observe the diffraction pattern produced on a luminescent screen. The lattice structure of the crystal causes electrons to diffract across the grid, forming a diffraction pattern of concentric circles. The pattern of concentric circles depends on the crystal's lattice structure as well as the wavelength of the incoming electrons. A series of alternating bright and dark diffraction spots can be observed, which is an interference effect caused by the wave nature of the scattered electrons.

The virtual electron diffraction experiment designed in this study allows learners to emit electrons from the electron gun by clicking the eject button and then observe that the electrons passing through the gold foil will produce diffraction patterns on the photographic film behind (Figure 6). Learners can switch the viewing angle to observe the electron beam projected onto the gold foil, where the crystal lattice acts as a diffraction grating to scatter the electrons in a predictable manner and result in a diffraction pattern.

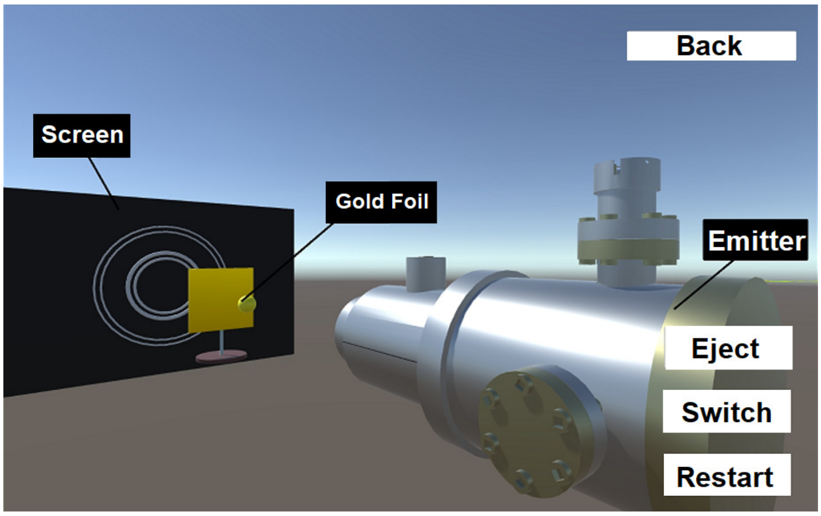

Figure 6. Virtual electron diffraction experiment.

3. Teaching Experiment

This study adopted the quasi-experimental pretest–posttest design of nonequivalent groups. A total of 60 students (ages 16–18) from an upper secondary school in Taoyuan, Taiwan, were recruited as the research subjects (Figure 7), 30 students in the control group (using the traditional teaching method), and 30 students in the experimental group (using the virtual teaching modules). The teaching method is the independent variable, and the learning effectiveness is the dependent variable, the pre-learning ability of quantum mechanics is the co-variable, and the control variables include the teacher, learning content, and teaching time. The purpose of this teaching experiment is to analyze the impacts of using different teaching methods on the learning effectiveness of quantum mechanics. Questionnaires were used to measure the learning motivation, cognitive load, and system satisfaction of the experimental group students. In addition, the researchers have collected the teacher's opinions after applying virtual reality to teaching, which can be used to improve the virtual teaching modules.

Figure 7. Research subjects: experimental group (**left**) and control group (**right**).

3.1. Learning Effectiveness

To explore the learning performance of using the virtual teaching modules, this study designed the achievement test (Appendix A) and invited physics teachers and experts to assist in analyzing the difficulty of the test items to ensure their validity as well as conforming to the teaching objectives and students' levels. In terms of reliability analysis, the test questions were tested by non-experimental students, and then the analysis of internal consistency was performed to remove unsuitable test items.

After the teaching experiment, the experimental results were analyzed by the analysis of covariance (ANCOVA) to explore the results of using the virtual teaching modules for learning quantum mechanics. The ANCOVA results show a significant difference between these two groups, with f = 32.94 and $p = 0.048 < 0.05$, indicating different learning methods have an impact on the learning outcomes. According to Table 1, the experimental group has more progress than the control group, indicating virtual reality is more effective than the traditional method in learning quantum mechanics. More precisely, virtual reality can improve the learning outcome of quantum mechanics.

Table 1. Descriptive statistics of both groups on achievement test scores.

Group	Pretest Mean	S.D.	Posttest Mean	S.D.
Experimental Group	6.73	1.93	10.07	2.70
Control group	7.73	2.57	9.60	3.03

3.2. Learning Motivation

The "Learning Motivation Questionnaire" used in this research adopts a five-point Likert scale, the score ranging from "strongly disagree = 1" to "strongly agree = 5," and the higher the score, the higher the learning motivation. This questionnaire was designed to evaluate the learning motivation of the virtual teaching modules of quantum mechanics, so it was only filled out by the experimental group. The overall average score of students' learning motivation is 3.97, approximating the score of "agree = 4."

From the statistical results in Table 2, we can see that the lowest average score among all questions is $3.57 > 3$, and the highest average score is $4.23 > 4$. The learning motivation is above the middle level, and three questions have average scores higher than 4. It is speculated that the characteristics of virtual reality, immersion, interaction, and imagination can allow visualization of the particles and wave phenomena of electrons and photons to improve the motivation of students in learning quantum mechanics.

Table 2. Statistical results of learning motivation scale.

Learning Motivation Questionnaire	Min	Max	Mean	S.D.
1. I think learning in virtual reality is fun.	3.00	5.00	4.17	0.75
2. I want to use virtual reality more for learning.	3.00	5.00	4.23	0.77
3. After studying with virtual reality, I think natural science is interesting.	1.00	5.00	3.67	1.15
4. I would like to actively use virtual reality to study sciences.	1.00	5.00	3.57	1.10
5. Compared with traditional teaching, I think using virtual reality is helpful to my study.	3.00	5.00	4.23	0.68

3.3. Cognitive Load

The "Cognitive Load Questionnaire" in this research uses a five-point Likert scale, the score ranging from "strongly disagree = 1" to "strongly agree = 5," and the lower the score, the lower the cognitive load. This questionnaire was designed to evaluate the cognitive load incurred by the virtual teaching modules of quantum mechanics, so it was only filled out by the experimental group. The overall average score of students' cognitive load is 1.85, a little lower than the score of "disagree = 2." The average value of each question is between 1.50 and 2.17. We can see from Table 3 that the cognitive load of the students using the virtual teaching modules is relatively low. As a result, virtual reality has a positive impact on the cognitive load of quantum mechanics.

Table 3. Statistical results of cognitive load scale.

Cognitive Load Questionnaire	Min	Max	Mean	S.D.
1. It is difficult for me to learn knowledge using virtual reality.	1.00	3.00	1.93	0.52
2. In this learning activity, I had to spend a lot of effort to answer the questions.	1.00	4.00	2.17	0.91
3. In this learning activity, answering questions made me feel very troublesome.	1.00	3.00	1.80	0.61
4. In this learning activity, answering questions frustrated me.	1.00	3.00	1.50	0.57
5. I didn't have enough time to answer questions.	1.00	2.00	1.60	0.50
6. In this learning activity, both the teaching method and the presentation of the learning content cost me a lot of brainpower.	1.00	5.00	2.03	0.96
7. In this learning activity, I had to put in a lot of effort to complete the learning objectives.	1.00	5.00	2.17	0.95
8. In this learning activity, the teaching style was difficult to follow and understand.	1.00	4.00	1.57	0.73

3.4. System Satisfaction

In order to understand students' opinions about using virtual teaching modules to learn quantum mechanics, this study conducted a questionnaire survey on system satisfaction using a five-point Likert scale for scoring (strongly disagree: 1 point, disagree: 2 points, general: 3 points, agree: 4 points, strongly agree: 5 points). The researchers discussed with experts and scholars to ensure the correctness of the questionnaire. The evaluation items of this questionnaire are divided into three parts: learning content, interface design, and system operation, containing a total of 14 questions (Table 4). The average score of all questions is 4.39, and the standard deviation is 0.43, indicating students were mostly satisfied with the virtual teaching modules.

Table 4. Statistical results of system satisfaction on teaching modules.

		Evaluation Items	Mean	S.D.
Learning Contents	1.	I understand the instructional description in the system.	4.57	0.57
	2.	I think the system allows me to learn quantum mechanics.	4.22	0.55
	3.	I think the system is helpful in acquiring new knowledge.	4.43	0.55
	4.	The system helps me get useful information when I need it.	4.17	0.59
Interface Design	5.	I think the user interface of the system is easy to operate.	4.23	0.68
	6.	I think the size of system operation panel is appropriate.	4.28	0.58
	7.	I think the animation is very similar to the real situation.	4.02	0.88
	8.	I think the 3D model is clear and the font size is proper.	4.28	0.82
System Operation	9.	It was not difficult for me to learn to operate the system.	4.53	0.54
	10.	It only took me a short time to master using the system.	4.65	0.46
	11.	The system mechanism makes the learning process smooth.	4.52	0.61
	12.	I think the system can help me learn better.	4.30	0.64
	13.	Using the system is more interesting than traditional ways.	4.58	0.67
	14.	I think the system adopts an easy and useful learning way.	4.60	0.65

4. Discussion

Quantum mechanics is a branch of physics to study the laws of motion of microscopic particles. It can explain the nature and behavior of matter and energy on the atomic and subatomic level, which is very different from the physics of the macroscopic world. In the cognition of quantum mechanics, all things can be in different states at the same time, and the results will appear when they are observed, but these results occur in a probabilistic manner. The impact of quantum mechanics has exceeded the scope of classical physics, bringing infinite possibilities to the world. It has changed the basic thinking of scientists, as well as people's intuition and traditional cognition.

Quantum effects play an important role in the research and development of many modern technological devices. For example, the stimulated emission proposed by Einstein is the basic principle of the laser light source generator; the electron microscope uses the wave–particle dual image of the electron to improve its resolution; the atomic clock calculates and maintains its time accuracy by using the frequency of the microwave signal emitted by electrons when moving to a higher energy level; the application of quantum theory to research on semiconductors led to the invention of diodes and transistors. Those mentioned above are the indispensable theoretical foundations for the development of modern electronic systems and high-tech equipment.

In this study, the teaching experiment was conducted at a senior high school, where the experimental group used a tablet computer for learning. Before starting the experiment, the researchers briefly explained the method, process, and precautions for operating the virtual teaching modules. After that, the students explored the learning content by themselves, and they could discuss it freely with other students or ask the teacher questions. There was a teaching assistant on site to observe the learning process and assist learners in solving questions at any time for the learning activity to proceed smoothly.

For the control group, the teacher taught according to the guidelines of instructional design, and the students followed the traditional teaching method to listen to the teacher's instruction. Compared with the experimental group, the control group asked fewer questions and discussed with each other on occasion during the experiment. However, the performance of the experimental group is better than that of the control group, according to the analysis results. It is inferred that the virtual teaching modules provide a scaffold for independent learning by making complex and abstract concepts observable and more impressive so they can improve learning effectiveness.

This study used virtual reality technology to concretize the abstract concepts of quantum mechanics and make them easy to observe. The teaching modules can provide an interactive and immersive operational environment, allowing learners to understand quantum theory through the photoelectric effect experiment. The cathode ray tube experiment shows that all atoms contain negatively charged subatomic electrons. The oil drop experiment can be used to calculate the mass and fundamental charge of electrons. The gold foil experiment displays that the atom contains mostly empty space and a tiny nucleus with a positive charge. The electron diffraction experiment shows that electrons exhibit wave behavior because they can be diffracted by a crystal structure.

According to the above experimental results, Bohr's atomic model can be used to explain the discontinuous spectral lines of hydrogen atoms, and Heisenberg's uncertainty principle shows that the momentum and position of a particle cannot be determined at the same time, which is of great help for understanding quantum mechanics. Learners can observe from complementary and multiple perspectives to deepen their learning impression by creating more intuitive and realistic experiences and attain a clearer understanding of the particles and wave duality of microscopic substances.

5. Conclusions and Suggestions

The virtual teaching modules developed in this study can transform the difficult and abstract quantum theory into an easy-to-understand learning experience. They are effective learning tools with a lower cost in construction and maintenance, and thus suitable for high school and college physics courses. They can be placed on the public website for teachers, students, and the general public to download for learning. This study's main goal is to achieve popularization through promotional activities for learners of different ages to know that quantum mechanics is not a difficult and abstract theory and then become willing to learn new concepts of modern physics.

5.1. Conclusions

In this study, virtual reality technology was used to develop teaching modules related to quantum mechanics, leading students to further understand the implementation process of famous experiments and increase their learning motivation about physics. Through this research, students' learning effectiveness was investigated by the teaching experiment to understand their performances and views on the virtual teaching modules. The following findings are obtained from the teaching experiment:

(1) *The virtual teaching modules can improve learning effectiveness.*

The ANCOVA results show that the experimental group using the virtual teaching modules performed better than the control group learned with the traditional teaching method, indicating virtual reality can enhance the learning effectiveness of quantum mechanics. Students can also become more familiar with the experimental process of quantum mechanics after using the virtual teaching modules.

(2) *The virtual teaching modules incur low cognitive load and high learning motivation.*

The statistical results show that the average score of students' learning motivation is 3.97, approximating the score of "agree = 4"; the average score of students' cognitive load is 1.85, lower than the score of "disagree = 2." It is speculated that the immersive and interactive virtual teaching modules can visualize the particles and wave phenomena of electrons and photons to reduce the cognitive load and increase the learning motivation of students in learning the concepts of wave–particle duality.

(3) *Users were mostly satisfied with virtual teaching modules.*

The questionnaire results on system satisfaction indicate that students had positive feedback about the virtual teaching modules, including learning content, interface design, and system operation. The average score of the questionnaire is 4.39, revealing that students were satisfied with the virtual teaching modules. Most students could understand the relevant knowledge and principles of quantum mechanics and become familiar with the experimental process after using the virtual teaching modules.

The virtual teaching modules can also be used to solve the calculative tasks in the field of quantum mechanics. For example, in the virtual oil drop experiment, we can calculate the greatest common factor from the charges of different oil drops to determine the basic charge carried by an electron. A similar application can also be found in learning the concepts of special relativity using virtual reality [23], where calculative tasks were performed by adjusting the spacecraft speed to observe the phenomena of time dilation and length contraction and determine the mass-energy equivalence.

5.2. Suggestions

In this study, the virtual teaching modules for learning quantum mechanics were designed using Unity 3D Game Engine for execution on a tablet computer. In the future, they can be upgraded by including the functions of a head-mounted display, three-axis accelerometer, electronic compass, and other components to enhance the interactive user interface of the virtual experiments. In that case, users can be more immersive in the virtual learning environment to further improve their learning effectiveness.

The virtual teaching modules of quantum mechanics were designed with the basic theories and important concepts of quantum mechanics. The questionnaire surveys on the learning motivation and cognitive load of quantum mechanics were conducted by the experimental group only. It is suggested that a more in-depth study be conducted in the future to compare the cognitive load and learning motivation between the two groups using a larger sample size so that the researchers can discover how the virtual teaching modules can reduce the cognition load and increase learning motivation by visualizing the phenomena of wave–particle duality and help learners understand the abstract concepts of quantum mechanics. Because the gender, age, and educational background of individual participants may also affect the effectiveness, motivation, and cognitive load in learning quantum mechanics, additional variables can be included in the future research design to obtain further findings by a more thorough investigation.

Although virtual reality is gaining increasing popularity in various applications, it still has some limitations and drawbacks. For example, immersive VR equipment is more expensive in comparison with tablet PCs, and its software requires more memory space and higher computing power, so the user needs a computer with a powerful CPU and graphics card for executing VR software. In addition, it is not suitable for students with VR motion sickness or 3D dizziness and, therefore, may affect the willingness to use VR software. The virtual teaching modules can be applied in other courses, and our future studies include the extension of virtual reality applications to:

- Simplification and visualizing complex robot kinematics theories: The teaching module can combine interactive games to stimulate the learning motivation and interest of students. Physical robot control can also be included to develop an integrated robot training environment. The learners can control the virtual robot to observe the execution results of the kinematics theory and then understand how to calculate the target position through the setting of the robot's joint parameters.
- Learning advanced semiconductor manufacturing technology: The lithography technology of electronic components has approached the limit of two-dimensional quantum mechanics, so the current research and development of the semiconductor manufacturing process has migrated to three-dimensional lithography technology. A virtual teaching module can be developed to visualize the complex knowledge and abstract concepts of semiconductor manufacturing technology.

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Appendix A

Achievement Test (18 multiple-choice questions)

1. In the α-particle scattering experiment, which of the following phenomena occurs after the α particle hits the atoms in the gold foil?

   (A) Randomly scattered
   (B) Hit straight on the fluorescent screen
   (C) Scattered at a fixed angle
   (D) The whole beam of α particles was refracted at right angles
   (E) α particles were absorbed by the atoms in the gold foil

2. Rutherford's atomic model is mainly based on which of the following experimental results?

   (A) Photoelectric effect experiment
   (B) Black body radiation experiment
   (C) Interference experiment
   (D) α-particle scattering experiment
   (E) Spectrum experiment

3. Which of the following experiments is the first to accurately determine the charge of an electron?

   (A) Franck-Hertz experiment
   (B) Thomson charge-to-mass ratio experiment
   (C) Millican oil drop experiment
   (D) Rutherford gold foil experiment
   (E) Millican photoelectric effect experiment

4. Which of the following is the cathode ray actually emitted by the cathode?

   (A) high-energy X-rays
   (B) electromagnetic waves with very short wavelengths
   (C) a group of α particles
   (D) electron beams
   (E) a group of hydrogen atoms

5. Regarding the cathode ray experiment, which of the following statements is correct?

   (A) The cathode ray is an α-particle beam.
   (B) The cathode ray can be deflected by changing the direction of the magnetic field.
   (C) The cathode ray will finally hit the glass opposite the cathode ray tube directly.
   (D) The cathode ray cannot be deflected by external factors.
   (E) Cathode rays are blue.

6. Which of the following is not related to the cathode ray?

(A) It is emitted from the cathode of the discharged tube.
(B) It can be attracted by the positive plate of the electric field.
(C) It is radiant energy.
(D) It is negatively charged.
(E) It can be bent by changing the electric field.

7. Which statement about cathode rays is not true?

(A) Cathode rays are negatively charged particles.
(B) Using different metals as cathodes, the resulting cathode rays have the same charge-to-mass ratio.
(C) Cathode rays travel straight and have kinetic energy.
(D) A cathode ray in an electric field is biased, and there is no bias in the magnetic field.
(E) All of the above

8. The photoelectric effect shows that light has

(A) volatility
(B) conductivity
(C) continuity
(D) particle property
(E) movement

9. If an electromagnetic wave is irradiated on a photovoltaic panel, and the photoelectric effect cannot be produced, then changing which of the following physical quantities of the electromagnetic wave can cause the photovoltaic panel to release photoelectrons?

(A) increasing wavelength
(B) increasing frequency
(C) decreasing frequency
(D) increasing intensity
(E) increasing power

10. When a photoelectric effect occurs on a photoelectric surface, which of the following is related to the number of photoelectrons irradiated?

(A) photon frequency
(B) light intensity
(C) photon wavelength
(D) photon energy
(E) photon speed

11. Which of the following statements about the photoelectric effect is true?

(A) When the frequency of the incident light is greater than a certain value, a photocurrent will be generated.
(B) No matter what frequency of light hits the metal plate, a photocurrent will definitely be generated.
(C) Increasing the light intensity will not increase the generated photocurrent.
(D) After increasing the light intensity, the photocurrent will decrease.
(E) When a plastic plate is illuminated by light, it can also generate photocurrent.

12. Which of the following is ejected by a photon in the photoelectric effect?

(A) atom
(B) proton
(C) nucleus
(D) electron
(E) neutron

13. Which of the following statements about atoms best fits the original claim of the Rutherford model?

(A) The atom has positive and negative charges.
(B) The positive charge in the atom is concentrated in the nucleus.
(C) 10% of the atomic mass is concentrated in the nucleus.
(D) The nucleus is mainly composed of protons and neutrons.
(E) The spectrum of hydrogen atoms is discontinuous because light has the characteristics of particles.

14. Which of the following experiments established an atomic structure model in which electrons orbit the nucleus?

(A) Thomson charge-to-mass ratio experiment
(B) Blackbody radiation experiment
(C) Photoelectric effect experiment
(D) Rutherford gold foil experiment
(E) X-ray crystal diffraction experiment

15. Which of the following is true about Milikan oil drop experiment?

(A) All oil droplets sprayed out in the experiment will fall into the electric field.
(B) A very small number of oil droplets will enter the electric field through the small hole of the positive plate.
(C) All oil droplets in the experiment will be suspended above the positive plate.
(D) All oil droplets will gather into one large oil droplet and fall into the electric field.
(E) All oil droplets will adhere to the wall of the container.

16. What kind of physical quantity is the main purpose of Milikan oil drop experiment?

(A) mass of electrons
(B) number of electrons
(C) size of electrons
(D) the charge-to-mass ratio of electrons
(E) electricity of electrons

17. In the electron diffraction experiment, which of the following patterns will be generated on the photographic film by the electrons emitted from the electron gun?

(A) square
(B) triangle
(C) concentric circles
(D) solid circles
(E) no pattern generation

18. In the electron diffraction experiment, the electrons emitted by the electron gun pass through which of the following to produce patterns on the photographic film?

(A) metal foil board
(B) white paper
(C) plastic board
(D) glass board
(E) wood board

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