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Experiencing Gravitational Red-shiftting in Virtual Reality

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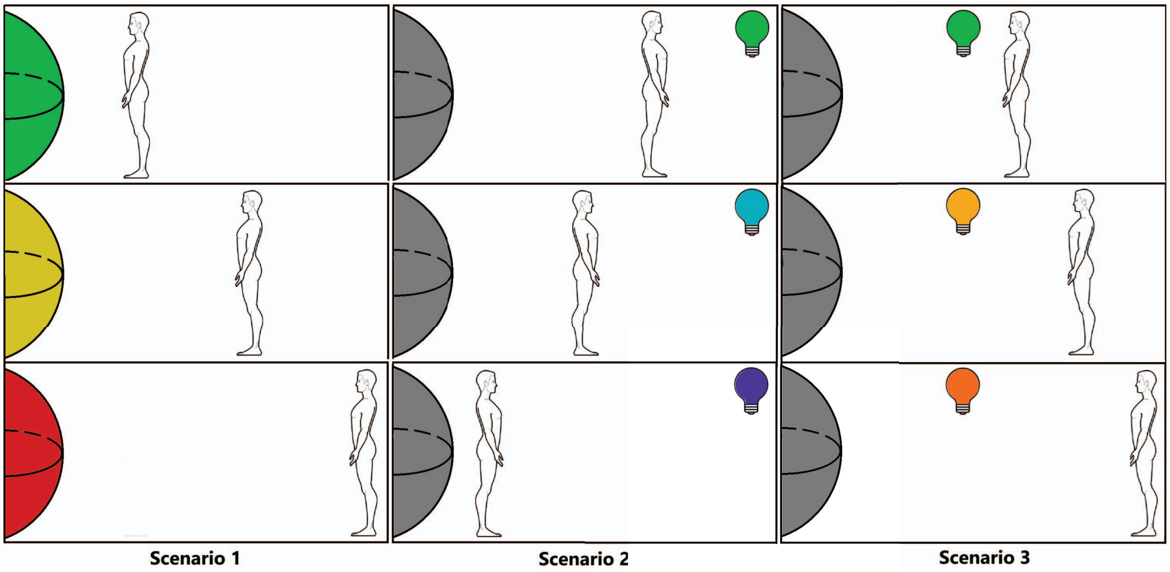

Figure 1: Scenario 1) The massive sphere emits photons with a wavelength of 500nm corresponding to the color green. If the observer is very close to the surface of this massive sphere, they observe it as green but as they increase their distance, photons become increasingly red-shifted. Scenario 2) In this scenario the light source is considered to have negligible mass in comparison to the massive sphere which causes the gravitational field. This light source emits photons with a wavelength of 500nm corresponding to the color green. As the observer increases their distance to the light source by moving toward the massive sphere, photons are blue-shifted. Scenario 3) In this scenario observer increases their separation from the light source by moving away from the massive sphere. As a result, the photons are red-shifted.

ABSTRACT

Gravitational red-shifting of light is of immense importance for physics students; however, in contrast to many other physics phenomena, it cannot be easily demonstrated in a conventional physics laboratory due to the immense scales involved. To provide students with an experiential learning tool for this otherwise abstract concept, we leveraged Virtual Reality (VR) and designed an innovative VR simulator featuring three distinct scenarios that allow users to directly witness this phenomenon.

Index Terms: Gravitational Red-shiftting—Physics—Experiential Learning—General Relativity; Virtual Reality—Extended Reality

1 INTRODUCTION

It is often highly challenging for students to grasp fundamental physics concepts and theories as they cannot visualize the phenomena and it is hard to observe directly in daily experiences [6, 14]. Extended Reality (XR) environments, encompassing Augmented Reality (AR) and Virtual Reality (VR), have the potential to effectively provide better visualization and interaction with real-like three-dimensional virtual objects for physics education [12]. XR aims to support students' understanding of underlying principles and phenomena while avoiding the teaching of formulas through rote memorization. Instead of solely instructing students on reciting formulas, the focus is on imparting the knowledge of how to apply and comprehend these formulas in practical contexts [23].

XR can enhance physics education in multiple ways: by visualizing abstract and complex physics concepts that are difficult to perceive in real environments through providing deeper insights [8,14,27,31], exploring different scales of physical worlds and materials, simulating physics environments when access to physical laboratories is limited or expensive [3], facilitating the experiments by providing virtual guidelines and information [13], capturing information without the time and space limitions [17, 20], achieving instant results [21], allowing to perform experiments that are not safe [24, 28], and providing interactive learning [10]. VR not only expands access to practical learning experiences but also allows students to repeat and modify experiments, reinforcing their understanding of scientific methodologies. In addition, the immersive nature of VR makes learning more engaging and increases students' motivation. The importance of using VR in physics education becomes even more highlighted when experiencing physics concepts that cannot be replicated even in physical laboratories. One such concept is the gravitational red-shifting.

The main contribution of this paper is presenting a VR envi-

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ronment that can be used to teach or learn the fundamentals of gravitational red-shifting. Using immersive VR simulations can provide significant aid in improving the learning process of this concept. One of the key significance of this research lies in the fact that, unlike many physics phenomena, the gravitational red-shifting of light cannot be demonstrated in a traditional physics laboratory due to the vast scales involved.

2 RELATED WORK

Extended Reality technologies are increasingly garnering attention in the realms of education and skill development. This heightened interest is evident in the creation of interactive learning environments, where XR finds application across diverse academic disciplines like cooking [26], biology [16], surgery [18], math, immersive analytics [7], physics, etc. Furthermore, XR modalities such as eye gaze, controllers, hand gestures, and virtual avatars play a pivotal role in enhancing interaction within these technological domains [4, 14, 25, 32].

Both AR and VR have been used in previous physics studies to improve the learning process for students. Dunser et al. introduced an interactive physics education book using AR to help students learn in learning physics and engage them more by overlaying virtual content over real book pages [10]. As an example, while students read the Right Hand Grip Rule in their book, virtual content pops up, and visualize the concept in 3D. Their results confirmed that AR has the potential to be effective in teaching complex 3D concepts [10]. In another study, authors developed a video see-through AR environment to simulate a system that provides the physical deformation and movement of 3D volumetric objects for educational purposes. Their findings showed that %93 of students (majoring in physics) would like to use the system for their education [29]. Akcayir et al. showed the positive effect of using AR in a physics laboratory by providing virtual information (e.g., animation and simulation). Their findings confirmed the effectiveness of using AR in increasing laboratory skills and improving students' work speed [1].

VR has attracted even more attention in physics education, and numerous previous studies have explored the benefits of using VR in enhancing physics understanding. Several previous studies implemented 3D virtual labs which are considered a low-cost alternative to educators and students [19, 21, 24]. These virtual labs allow students to study the virtual assembly of instruments, the realization of dynamic 3D gauges, the setup of emulation-based systems [19], Electronics and magnetism [21], nuclear physics [28], Special Theory of Relativity [30, 31], etc.

In 1993, Brelsford conducted a comparison between a VR-based physics educational system and traditional methods such as teacher-organized or computer-aided learning [5]. The experiment utilized a controllable-length pendulum and three balls of identical size, each with variable mass, to impart physics concepts related to gravity, mass, and friction. The results revealed that VR-based learning outperformed traditional lecture-based control conditions. In another study, researchers employed VR to simulate the water cycle in nature, investigating physics phenomena like vaporization and condensation. The findings from 58 primary school children indicated that the majority of the students not only found the application useful but also enjoyed learning the presented topics [2]. Table 1 provides a summary of several previous studies in physics education that used XR to enhance the learning process.

Table 1: Previous related works used XR for physics education

Ref	Year	Physics Focus	XR
This study	2024	Gravitational red-shifting of light in general theory of relativity	VR
[31]	2021	Special theory of relativity	VR
[30]	2021	Time dilation in special theory of relativity	VR
[27]	2020	The solar system (the orbital path of each planet)	VR
[28]	2020	Nuclear physics	VR
[23]	2019	Physics laboratory (e.g. Van de Graff generator with balloon)	VR
[13]	2019	Electromagnetic	VR
[29]	2019	Real-Time physics simulator (to study force)	AR
[21]	2018	Virtual electronics laboratory	VR
[2]	2018	Vaporization and condensation in water cycle field	VR
[15]	2017	Mechanics and forces, electricity and magnetism, the structure of matter	VR
[1]	2016	Electricity	AR
[19]	2015	Realization of dynamic 3D gauges and the setup of emulation-based systems	VR
[10]	2012	High-school physics books concepts	AR
[9]	2007	Electricity and magnetism	VR

2.1 Experimental and Active Learning

Freeman et al. have found that active learning is a helpful approach in improving students' performance and learning results compared to more traditional methods [23]. Active learning is a method that requires students to actively take part in the learning process instead of just sitting and listening to the teacher's speech. Active learning can enhance students' problem-solving skills in physics education by engaging students in the learning process with hands-on experiences rather than on reciting theoretical concepts or memorizing formulas [23]. VR is a perfect choice for experimental and active learning in physics.

3 THEORY

Gravitational red-shifting is a phenomenon predicted by Einstein's theory of general relativity [11, 22]. It occurs when light or electromagnetic radiation travels through a gravitational field, such as that of a massive object like a star or a black hole. The gravitational field affects the wavelength (and hence the energy) of the photons, causing a shift toward the red end of the electromagnetic spectrum when the photon travels away from the massive object. Conversely, there is a shift toward the violet end of the spectrum when the photon travels toward the massive object.

A massive sphere generates a spherically symmetric gravitational field. Wavelength of a photon traveling in such gravitational field changes according to formula 1.

$$\lambda(r_{\text{observer}}) = \lambda_{\text{source}} \sqrt{\frac{1 - 2\frac{GM}{c^2 r_{\text{observer}}}}{1 - 2\frac{GM}{c^2 r_{\text{source}}}}} \qquad (1)$$

where:

- r_{observer} is the distance between the center of the massive sphere and the location of the observer.
- r_{source} is the distance between the center of massive object and where the photon is emmitted.
- $\lambda(r_{\text{observer}})$ is the in light wavelength as received by an observer at location r_{observer},
- λ_{source} is the initial wavelength of the light at the source,

- G is the gravitational constant ($6.67430 \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$),
- M is the mass of the object causing the gravitational field,
- c is the speed of light (3×10^8 m/s),

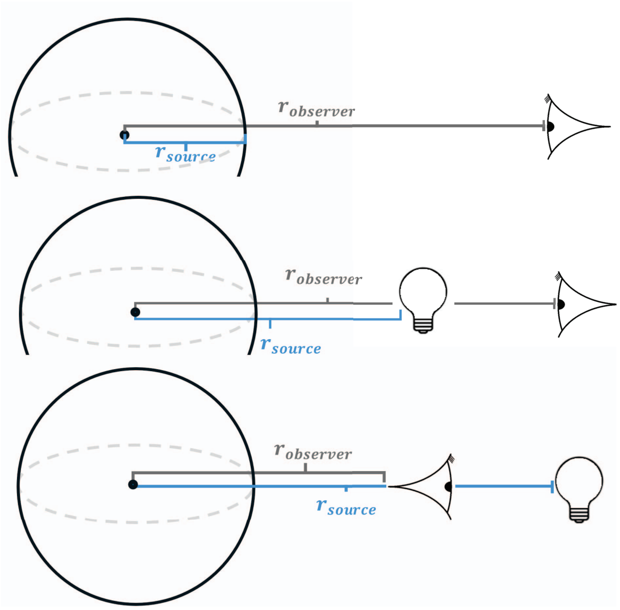

Figure 2: The position of the observer and light source (massless object) with respect to the center of the massive sphere. Scenarios 1, 2, and 3 from top to bottom, respectively.

Where the position of the observer and light source is measured from the center of the massive sphere as depicted in Figure 2. To put it in words, in a gravitational field, when a light source (such as surface of a star or, in this study, a light bulb!) emits a photon, which is a light particle, wavelength[1] of the emitted photon changes as it travels in the gravitational field. Human eye can detect a range of light wavelengths and associate them with colors as shown in the left two columns of Table 2.

4 METHOD

In this project, we designed multiple scenarios for the user to experience the concept of gravitational red-shifting. What is meant by a scenario is an arrangement of 'massive' and 'massless' objects and light sources. The mass of a 'massless' object is assumed to be negligible with no effect on the gravitational field generated by the 'massive' object. A VR Head Mounted Display (VR-HMD) allows a participant to move and observe objects from different positions. The user can observe objects changing colors as their position change in the environment and as the relative position of other objects in the environment changes. What follows is the description of each of the three scenarios.

4.1 First Scenario

This scenario is the most elementary scenario with a minimal environment. The only object in this environment is a massive sphere as depicted in the left column of Figure 1. In this scenario, the massive sphere emits photons from its surface in addition to generation the gravitational field. An observer can approach toward or away from the sphere. The user observes this sphere in different colors depending on the distance between the user and the sphere.

The massive spherical object emits light rays with a wavelength of 500 nanometers from its surface. If someone looks at the surface with no separation between the observer and the surface of the sphere, they observe this wavelength as color green. Light rays travel from the surface to the observer through the gravitational field and depending on how far this travel is, photons lose energy, and thus the light wavelength increases.

In scenario one, light is emitted at the surface of our massive sphere at the wavelength of 500nm. Let's consider that the sphere's mass is $M = \frac{c^2}{2G} \approx 1.4 \times 10^{27} kg$, placing it in the same order of magnitude as Jupiter's mass or a thousand times less than the mass of the sun. However, for the purpose of this study, we assume that the radius of our massive sphere is only $2m$. In the first scenario, our massive sphere emits light from its surface. That means $r_{source} = 2m$. Then equation 1 gives us the following formula for observed wavelength in scenario one:

$$\lambda(r) = 500\sqrt{\frac{1 - \frac{1}{r_{observer}}}{1 - \frac{1}{r_{soruce}}}} \qquad (2)$$

Figure 3 shows how the object is observed from different distances. Depending on the distance from the object, it is seen in different colors. As the observer moves away from the object, its color shifts toward red.

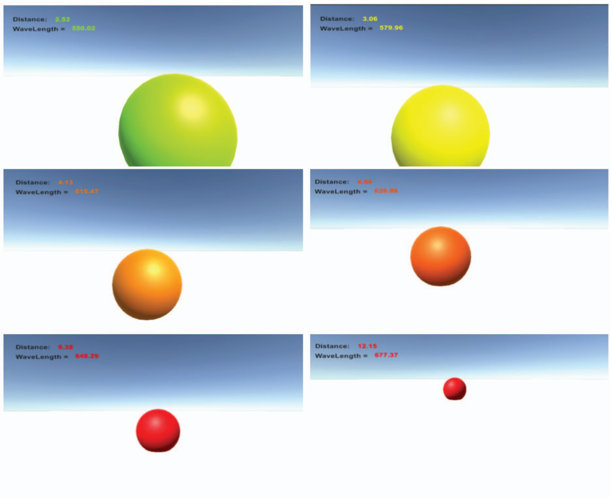

Figure 3: Massive sphere emits photons with wavelength 500nm corresponding to the green color. As the observer moves away from the massive object, the massive object appears smaller, and its color changes as well. When the observer is standing very close to the massive object, there is not much of a Red-shifting effect and the massive sphere is observed as green but as the separation between the observer and the massive object increases light is more and more red-shifted.

4.2 Second Scenario

There are two objects in the environment; One massive sphere causing the gravitational field similar to the first scenario but it doesn't emit any light. The second object has negligible mass and emits photons with $\lambda_{\text{source}} = 500nm$. We will call this object the light source or the massless object interchangeably. We are interested in the color of the latter object as observed from different positions. The color of the massive sphere was the subject of interest in scenario one and

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[1] Wavelength is the distance between successive peaks (or troughs) of a wave. Shorter wavelengths correspond to higher energy and vice versa.

it is ignored in this scenario. Here we first explain this scenario in the case where the observer stands in between the two objects.

Scenario 2, as depicted in the middle column of Figure 1, considers the case where the observer is positioned between the two objects and moves between the massive and massless objects. Let's suppose the light source is positioned at a distance of $15m$ from the center of the massive sphere, or equivalently, $13m$ from its surface. As depicted in Table 2, if the observer chooses to approach the massive object and increase their distance from the massless object, they will notice that the massless object's color shifts toward blue. On the other hand, if they decide to approach the massless object and move away from the massive object, they will notice that the massless object's color changes toward green.

4.3 Third Scenario

The setup of the third scenario is the same as the setup of the second scenario except that the light source is positioned between the observer and the massive sphere, as depicted in the right column of Figure 1. Let's suppose the light source is positioned at a distance of $3m$ from the center of the massive sphere, or equivalently, $1m$ from its surface. When the observer is close to the light source, they observe it to be bluish green and when they are far from it, they observe it to be red as depicted in figure 4 and Table 2.

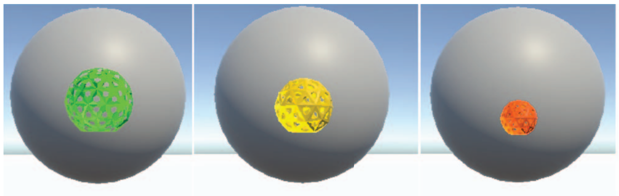

Figure 4: A light source with negligible mass emits photons with wavelength 500nm corresponding to color green. As the observer moves away from both the massive sphere and the massless object, the size and color of the latter object change as it appears from the observer's point of view. When the observer is standing very close to the small object, there is not much of a Red-shifting and it is observed as green but as the separation between the observer and both the massless object and massive sphere increases, light needs to travel out of the gravitational field toward the observer longer and longer distances and hence is more and more red-shifted.

Scenario 3 is essentially a variant of scenario 1. We introduced Scenario 3 specifically for the purpose of comparing it with scenario 2. When examining these two scenarios, one can note that even with the same separation between the light bulb and the observer, the observer perceives the light bulb in a markedly distinct color due to the difference in where they are relative to the massive sphere. In other words, the color in which the light source is perceived is a function of the positioning of all objects.

5 IMPLEMENTATION

The VR environment is developed using the Unity game engine for building the application. Unity comes with a built-in physics engine called Unity Physics. This allows developers to employ physics components and features of Unity to simulate realistic interactions between game objects. Rigidbody components, colliders, gravity, and joints are some of the tools provided for physics simulations. We used baked lighting techniques in the game engine with limited use of real-time lighting, as real-time lighting is computationally more demanding and it can have a negative impact on the performance. In addition, the XR Plugin Management for developing the VR environment and a free low-poly asset from the asset store called "Dining Room" is used for creating the massless object.

Table 2: The left two columns depict how the human eye associates colors with light photons of varying wavelengths. The right three columns illustrate that, depending on the relative positions of the massive sphere, light source, and observer, the light source appears to exhibit different colors even though in all scenarios, the light source emits only green photons with a wavelength of 500nm. Note that depending on the scenario the range of feasible wavelengths change. All distances are relative to the center of the massive sphere.

Color	Wavelength range (nm)	Scenario 1 (m)	Scenario 2 (m)	Scenario 3 (m)
Violet	380-450	1.40-1.68	2.17-4.10	-
Blue	450-495	1.68-1.96	4.10-11.73	-
Green	495-570	1.96-2.86	11.73-15	3-7.49
Yellow	570-590	2.86-3.30	-	7.79-13.94
Orange	590-620	3.30-4.33	-	13.94 $\geq$
Red	620-750	14.33 $\geq$	-	-

Users can utilize an Oculus Quest to explore the virtual environment. We selected the Oculus Quest for developing the VR environment because it is a mobile HMD that enables users to effortlessly experience our VR application on their headset without requiring a dedicated GPU. This ease of access makes it an ideal choice for our next step which is a human-centric experiment to evaluate our system and its effects on user performance and engagement. Users can change their position via directly walking or Controllers to move around the virtual object. This is especially useful for exploring the effect of red-shifting in long distances.

6 CONCLUSION AND FUTURE WORK

Understanding gravitational red-shifting is crucial for physics students, particularly those interested in cosmology. It connects theoretical principles to observational phenomena, offering valuable insights into the interplay between gravity and light. The research introduces a VR tool designed to enhance comprehension of gravitational red-shifting, an abstract phenomenon not observable in a traditional physics laboratory on Earth.

Using our tool, students can study and experiment with this concept through three different scenarios to obtain a more intuitive and experiential understanding of this abstract concept. For the next phase, we intend to carry out a human-centric experiment to assess the impact of the proposed system and active learning on enhancing participants' performance and engagement.

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