How augmented reality enhances typical classroom experiments: examples from mechanics, electricity and optics

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Abstract
Real situations are overlaid with virtual information using augmented reality technology. In a learning environment, this technology could give everyday relevance to abstract concepts. In this paper, we will show how physical structures in typical experiments can be simply augmented by virtual objects in physics classes. This is achieved by modelling objects with the GeoGebra software and overlaying visualisations of non-tangible, physical properties such as force arrows, colour-coded potential and light rays. Using the GeoGebra 3D Calculator app on a smartphone or tablet, these models can be displayed on any surface seen through the camera and dynamically adapted to real structures such as inclined planes, simple circuits or plane mirrors. As a result, elements that are normally not observable are visualised and contribute to understanding the phenomenon. Based on these ideas, further so-called augmented reality experiments can be devised from these examples. Augmenting real experiments with representations of physical concepts should enable students to see the world through the lens of a scientist and gain a deeper understanding.

Keywords: augmented reality, modelling, visualisations, representations

1. Visualisation of scientific concepts
Visualisation of concepts and problems is essential in a subject like physics. Throughout the history of science, visualisations have provided simple explanations for complex phenomena. They help to recognise patterns, gain insights and express what is in the mind’s eye, be it concrete or abstract. Like Newton’s famous illustration of
centripetal forces with the motion of projectiles around the earth, visualisations often illustrate ideas or even hypotheses to be tested in the future.

Since not everyone can develop new scientific ideas from their imagination, we believe students must know what they are looking for to recognise the core of a phenomenon. For this reason, step-by-step drawings at the board still play an important role in physics teaching. Teachers try to visualise either abstract concepts or experimental setups. In both cases, they add objects that are not visible in reality but help to understand the physics behind the experiment. According to the scientific discovery as dual search (SDDS) model of the scientific reasoning [1], this can also be seen as a possible environment to explore the hypothesis space before experimentation begins. This process has two main components:

(a) Construction of a model that contains possible interactions between certain variables (generate frame).

(b) Using concrete values to generate predictions (assign slot values).

As shown below, both steps can be substantially facilitated by using dynamic mathematics software.

1.1. Dynamic mathematics software

Mathematical terms and geometrical constructions occur in all areas of science as tools for formulation and visualisation of general theories and situation-specific models. Using dynamic mathematics software such as GeoGebra (www.geogebra.org) simplifies their construction and enables activities to effectively explore them [2]. Changes to an object in the model affect all related objects. In this way, the entire construction can be interactively influenced via variable parameters, programmed into the GeoGebra model. We call this type of applets dynamic models. The software enables the implementation of learning activities, whereby learners can independently create or edit dynamic models to gain verifiable hypotheses.

It is not just the search in hypothesis space that can be improved by GeoGebra. Testing and evaluating hypotheses in an experiment can be enhanced using augmented reality (AR) technology too.

1.2. Augmented reality

AR means augmenting the real environment with virtual objects. To achieve this, either the camera view on a screen or the view through a headset is overlaid in real-time. When the position of the mobile device or the headset changes, the virtual objects remain in its assigned position. In this way, their presence in the room appears almost natural. By overlaying real situations with digitised information, AR can help explain abstract concepts by linking them to tangible environments [3].

In addition to real elements, digital media increasingly supplements classroom experiments and other learning activities with digital information and virtual elements (from both simulated and measured values). We use the term virtual to refer to theoretical or preliminary considerations and computer-generated representations. Based on the taxonomy for immersive technologies [4], we find it useful in education not only to differentiate between real and virtual space or real and virtual objects but also between real and virtual content imparted by the learning activity (table 1).

In the context of this classification, we refer to AR experiments as partially digitised experiments that take place in real space and in which real objects are explicitly not replaced by virtual ones. Instead, real structures of the experiment are augmented by virtual objects, whereby unobservable elements contribute to the understanding of the experiment. For this purpose, we use visualisations of abstract scientific ideas and concepts that are constructed as dynamic models in GeoGebra. They impart virtual content that helps to understand the occurrence of real content such as observations and measurements.

Dynamic models created with GeoGebra can be opened with the GeoGebra 3D Calculator app on a smartphone or tablet. Without special markers, they are superimposed onto every area that is recognised by the camera by simply pressing the AR button. Compared to other AR apps that are geared towards a certain topic, higher motivation of both practitioners and learners can be expected as they can insert their independently created or
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### Table 1. Definitions of real and virtual characteristics of a learning activity.

| Real | Virtual |
|------|---------|
| **Space** | The activity… | The activity… |
| … takes place outdoors or indoors. It is perceived in real-time, either via an AR headset or on the screen of a mobile device with AR. | … takes place on the screen of a computer or a VR headset. It consists of an artificial 2D or 3D environment or it is a picture or video of a non-present real space. |
| **Objects** | … is conducted with objects and materials that exist in the real world. They are placed in real space or they were modelled in virtual space as precisely as possible. | … is conducted with artificial objects and materials. They are visualisations in virtual space or exist as a representation of abstraction in real space. |
| **Content** | … imparts phenomena that are perceptible with the senses. They are based on phenomenological descriptions and contain only observable elements. | … imparts theoretical ideas that are formulated in models. They are based on scientific concepts and rely on unobservable elements. |

Edited dynamic models into a real environment. Appropriate implementation of augmented reality in the classroom as explained in the following has the potential for great effects on learning.

## 2. Examples of AR experiments

We compiled a GeoGebra Book with AR instructions and experiments from mechanics, electricity and optics ([www.geogebra.org/m/pafx6xfu](http://www.geogebra.org/m/pafx6xfu)).

For each experiment, the real and virtual elements are discussed below. Based on the same teaching method, further AR experiments can be devised.

### 2.1. Mechanics

The two-dimensional and dynamical (2DD) approach to mechanics uses arrows to introduce basic kinematic quantities. In the following, they represent the direction and magnitude of velocity $\vec{v}$ and force $\vec{F}$ [5]. Formulating the relationship between additional velocity $\Delta \vec{v}$, mass $m$ and duration $\Delta t$, Newton’s second law is given as

$$\vec{F} \cdot \Delta t = m \cdot \Delta \vec{v}. \quad (1)$$

Mechanics curricula typically contain the analysis of forces on objects on inclined planes. Without friction, the magnitude of the resulting force on a cart can be measured depending on the angle of inclination $\alpha$ using a force meter. A mathematical expression for the resulting force can be derived based on the gravitational force $\vec{F}_G$ and geometrical considerations giving

$$|\vec{F}_R| = |\vec{F}_G| \cdot \sin \alpha. \quad (2)$$

A resulting force $\vec{F}_R$ can also be obtained by adding the force arrows of two or more forces. From a physical perspective, a description of the resulting force as the addition of gravitational and normal force $\vec{F}_N$ would be more appropriate:

$$\vec{F}_R = \vec{F}_G + \vec{F}_N. \quad (3)$$

In both cases, there are no visible signs of these quantities in the real experiment (table 2). However, this virtual content can be visualised using force arrows as virtual objects in an AR experiment. Furthermore, the concept of adding force arrows can be confirmed quantitatively (figure 1). To achieve this, the mass of the cart and the angle of inclination must be set in the model corresponding to the setup. To justifiably call this an experiment, the results must be compared several times by varying mass and angle.

When carrying out, it is obvious that there is friction between the object and the inclined plane. This can be used to explain systematic deviations that are not related to the accuracy of the measurement and alignment of the model.

### 2.2. Electricity

Dealing with voltage as a potential difference before talking about electric current has been...
proven to improve learning outcomes in comparison with traditional teaching methods when introducing electricity [6]. The electrical potential (or so-called electric pressure) is visualised using different colours and intensities. According to this approach, a battery maintains electric pressure difference by pumping electrons from one part of the circuit and pumping them into another. Consequently, there is always a maximum potential difference between the poles and the parts of the circuits connecting to them, which is shown by maximal colour difference of blue and red.

In a simple circuit, conductors of different colours are connected with a resistor, such as a light bulb. As a result of the potential or pressure difference, electrons flow through the resistor and make the lamp light up. To understand how the potential changes in the light bulb or within another resistor, it is useful to analyse a thin constantan wire in a circuit.

Between two points of a wire, different voltages $V$ can be quantified as:

$$V = V_0 \cdot \frac{\Delta l}{l_0}, \quad (4)$$

depending on the applied voltage $V_0$, the length of the wire $l_0$ and the distance between the two points $\Delta l$.

On the other hand, the measured voltage can be explained with different electrical potential at various points within the constantan wire. Between the ends of the wire, we assume a maximum potential difference $\Delta \phi_{\text{max}}$ from negative to positive numbers based on the applied voltage. As a result, we are expecting a zero potential in the middle.

$$\Delta \phi_{\text{max}} = \phi_+ - \phi_- = \frac{V_0}{2} - \left(-\frac{V_0}{2}\right) = V_0. \quad (5)$$

The voltage between two points of the wire can be explained by the potential difference $\Delta \phi$:

$$\Delta \phi = \phi_2 - \phi_1 = V_0 \cdot \frac{x_2}{l_0} - V_0 \cdot \frac{x_1}{l_0} = V. \quad (6)$$
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Table 3. Real and virtual objects and content of a simple circuit.

| Objects         | Real                  | Virtual                                      |
|-----------------|-----------------------|----------------------------------------------|
| Content         | A constantan wire     | Colour-coded electrical potential            |
| Measurement of  | of the voltage between | Visual and quantified potential differences   |
| two points of    | the wire              |                                              |
| the wire        |                       |                                              |

Figure 2. Experimental setup viewed through a smartphone during an AR experiment concerning potential differences.

Table 4. Real and virtual objects and content of a plane mirror.

| Objects | Real                  | Virtual                                      |
|---------|-----------------------|----------------------------------------------|
| Content | A coin                | Point object and light rays                  |
|         | Observation of the    | The intersection of extended reflection      |
|         | mirror image of the   | rays                                         |
|         | coin                  |                                              |

with $x_1$ and $x_2$ as positions of the two points at which the voltage probes are attached with $x = 0$ in the middle of the wire, where a zero potential is assumed.

Once again, invisible and abstract entities are used as arguments to understand observable phenomena physically (table 3). In an AR experiment, we can visualise the concept of electrical potential with colour-coded segments from intense blue for $\varphi_-$ and intense red for $\varphi_+$ (figure 2). Between the two extreme potentials, the intensities of the colours decrease and approach white at zero potential.

This kind of understanding of circuits is again confirmed by measurements in the real experiment. If the voltage is measured between any other two points with the same distance as in figure 2, the same value can be registered. In this case, however, it is calculated from other values for the potential, as can be seen in the dynamic model.

It should be noted that the model does not fully correspond to reality: the greater the resistance of the conductors used, the smaller the maximum potential difference at the ends of the wire. Therefore, a variable voltage source must be regulated upwards until the desired voltage prevails. As an alternative, a linear rheostat with a greater resistance could be modelled and augmented instead of the wire.
2.3. Optics

In geometrical optics, ray diagrams serve as a tool to solve and understand optical phenomena. However, they can cause many misconceptions [7]. Because light rays are just (virtual) elements of a model (according to our differentiation), students should not get the impression that light consists of individual rays.

In everyday situations, for example, when an object is in front of a plane mirror, light rays cannot be observed, but the mirror image (table 4). Using equal distance to the mirror axis, there is once again a mathematical method to find the position of the mirror image. On the other hand, it is possible to determine it using ray diagrams and the law of reflection in an AR experiment (figure 3).

Visualised rays from object point O hit the mirror axis. At every point P, the mirror reflects the rays according to the law of reflection. The extensions of the reflected rays intersect at one point behind the mirror. This point is exactly above the mirror image of the coin. Furthermore, the modelled intersection of the extended rays can be marked on the paper and compared with the location of the coin in reality. Students should also experiment with different positions of the coin directly in front or even off to the side of the mirror.

The location of the mirror image is again shown via the intersection of the extended rays. After the position has been set in the model, the reflected rays indicate the direction from which the mirror image is still visible.

On closer inspection, there are also numerous idealisations in this model that can be discussed in class: For example, the coin is not a point object and not all conceivable rays are shown (especially those not in the plane of the table). Nevertheless, the model serves the purpose of predicting the location of the mirror image using selected rays. The same concept is later used for optical imaging.

3. Conclusion and perspectives

With the geometry software GeoGebra, constructions can not only be made efficiently but also developed into dynamic models. The widespread access of learners to mobile devices also allows them to actively design their own models.

The use of AR mode in the GeoGebra 3D Calculator app enables learners to embed virtual objects in real space. Instead of imitating reality or displaying digital measurements, we propose overlaying reality with objects that have explanatory power such as force arrows, colour-coded potential and light rays. Many other experiments can be explained using the same virtual elements. Additionally, the general purpose of models in science can be demonstrated using AR experiments. This should enable students to see the world through the lens of a scientist and gain a deeper understanding.

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