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Making the invisible visible: Visualization of the connection between magnetic field, electric current, and Lorentz force with the help of augmented reality

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When introducing electromagnetism in schools, one specific experiment is inevitable: the force on a current-carrying conductor. Predicting the direction of the Lorentz force, the orientation of the magnetic field, and the direction of the electric current often causes difficulties for students. Here we present visual concept-relevant augmentations of the experiment that use the Microsoft HoloLens, which intends to counteract common students' misconceptions by taking relevant principles of educational psychology into account.

Theoretical background

Maxwell's equations[1] can completely describe the electrodynamics based on interaction of fields. Gauss's law of a magnetic field ***B*** is Maxwell"s second equation for the magnetic flux:

$$\oint_S \boldsymbol{B} d\boldsymbol{A} = 0. \qquad (1)$$

It can be clearly interpreted as the fact that there are no magnetic monopoles and that magnetic field lines always form closed loops.

Maxwell's fourth equation is formulated in the sense that an electric current I or a changing electric flux generates a circulating magnetic field:

$$\oint_l \boldsymbol{B} \cdot d\boldsymbol{s} = \mu_0 I + \varepsilon_0 \mu_0 \frac{d}{dt} \int_S \boldsymbol{E} \cdot d\boldsymbol{A}. \qquad (2)$$

Complementing Maxwell's equations with the Lorentz force can describe all (classical) electrodynamic phenomena. This Lorentz force F_L results from the vector product of the charge Q, which passes through a magnetic field B with velocity v:

$$\boldsymbol{F}_L = Q\boldsymbol{v} \times \boldsymbol{B}.$$

For a current-carrying wire section of length $\boldsymbol{dl}$, this equation can be transformed using the relation

$$Q\boldsymbol{v} = Q\frac{d\boldsymbol{l}}{dt} = \frac{dQ}{dt} d\boldsymbol{l} = I \cdot d\boldsymbol{l}$$

in the equation of the Lorentz force, which acts on a conductor with current I:

$$\boldsymbol{F}_L = I \cdot d\boldsymbol{l} \times \boldsymbol{B}.$$

Experimental setup and procedure

In the experiment of a current-currying conductor, students can directly explore the phenomena that are formally described by Maxwell's equations. Figure 1 shows the usual setup with a freely suspended current-carrying conductor placed in the magnetic field of a horseshoe magnet. A power supply generates a current of 10 A in the conductor swing.

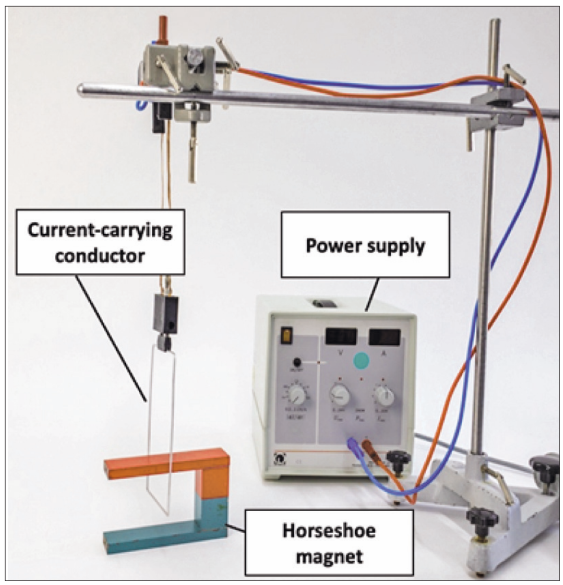

Fig. 1. Experimental setup for the demonstration of the Lorentz force.

Two problems arise for our students in this experiment. First, field effects on current-currying conductors are invisible. Second, split attention effects following from the discontinuity of relevant information impairs learning, because related additional representations such as vector representation, formulas, and magnetic field lines are presented at a spatial or temporal distance from the experimental setup (e.g., on the blackboard after experimenting). As a result, students either completely ignore invisible fields, misinterpret models of the invisible fields, or they incorrectly predict directions of interaction and movement. Therefore, the representations and their directions of interaction might help students to develop physically correct mental concepts and problem-solving strategies.

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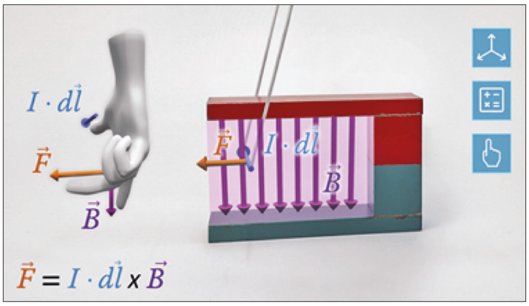

Fig. 2. Visualization of the magnetic field and the right-hand rule using the HoloLens. Optionally, three learning tools can be displayed: the formula of the Lorentz force, directional indications with the right hand, and the vector triad.

We address this with augmented reality (AR), as shown in Fig. 2. Based on prior work,[2-6] we use a HoloLens[7] to combine a virtual visualization with the physical experiment. Using these mixed-reality glasses, we create an interactive learning environment that follows well-established multimedia learning design principles.[8] This not only makes static invisibilities visible, but also allows students to directly experience physical relationships and processes because they see in real time how the parameters they modified dynamically influence other variables, processes, and fields. Thus, we obtain spatial and temporal contiguity between reality and its virtual representations to reduce a spatial and temporal split of students' attention during the experiment.[9]

As Fig. 2 shows, the HoloLens virtually visualizes the model of the magnetic field lines directly around the magnet. The model of the magnetic field combines a continuum with the directional magnetic field lines to prevent the misconception that there is no field between the lines. Corresponding vectors, field lines, and physical quantities in the formula are displayed in the same color. This color-coding helps students relate corresponding representations to each other. In addition to the presented experiment, the magnetic field around the conductor swing will be visualized. This allows students to observe the superposition and interaction of several magnetic fields.

To study the dependence of the Lorentz force F_L on the parameters of the electric current I and the conductor length dl, we subsequently manipulate each variable while keeping the others constant.

Results and outlook

Depending on the direction of the current, the current-carrying conductor moves to the left or right (see Fig. 2). In physics education the right-hand rule is used to illustrate the direction of the Lorentz force, which is the cause of this movement. This rule illustrates that the Lorentz force is the result of the cross product of the direction of the electric current and the orientation of the magnetic field. As there are country-specific variations of this rule, we follow the convention shown in Fig. 2: The right-hand thumb points in the technical current direction, the corresponding index finger is oriented parallel to the magnetic field lines, and the middle finger predicts the direction of the Lorentz force. All three fingers are orthogonal to each other like a vector triad. Whereas the movement of the current-carrying conductor becomes visible, the magnetic field of the horseshoe magnet, the electric current flow, and the related magnetic field around the conductor swing remain invisible. By subsequently studying the dependence of the Lorentz force F_L on the parameters of the electric current I and the conductor length dl, students can learn that the Lorentz force is proportional to the electric current I and the conductor length dl.

While the visualization of invisible, abstract variables should lead to better learning, the multitude of representations that can possibly be integrated may also increase cognitive load. Therefore, future work should investigate which forms of representations maximize students' learning and how many representations are optimal to maximally support students without cognitively overloading them.

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