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Interactive Physics Simulations in a Room-scale Virtual Laboratory

Master's Thesis

to achieve the university degree of

Diplom-Ingenieur

Master's degree programme: Computer Science

submitted to

Graz University of Technology

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Graz, September 2019

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Abstract

Nowadays, our life is characterized by rapid changes and new technologies. Skills in science, technology, engineering, and mathematics are increasingly in demand. Therefore, it is necessary to improve the learning methods in these fields. Theoretical knowledge and formulas are often not sufficient to understand complex physical phenomena such as magnetism, induction, or wave propagation. Simulations, instead, are a valuable method to visualize physical phenomena. They give a better understanding of how these phenomena work by involving the user directly in the learning process through interactions with the virtual world. This active learning approach has proven to be an effective learning method compared to traditional methods. Using new technologies allows meeting the needs of the new generation, which is accustomed to access and receive information very quickly. Current learning methods already use information and communication technologies to impart knowledge. Virtual experiences help to overcome individual limits given by the power of imagination. While virtual worlds are simulated places which can be visited, virtual reality opens an immersive way to explore virtual worlds. The constant interaction with the learning material is an essential factor in learning. Virtual reality technologies allow interaction with the virtual environment and enable a high intensity of immersion. This opens a great potential to develop motivating and engaging learning experiences.

This thesis introduces the design and conceptual model of the immersive physics laboratory Maroon and the experiments integrated into this framework. Maroon is designed as an interactive, extensible, virtual laboratory environment and allows the creation of different learning modules loaded into learning stations. The learning environment supports multiple technologies with different interaction, engagement and immersion levels. The room-scale VR version is a special extension of Maroon with immersive elements to draw attention to the learning content. The integrated experiments should help students to get physical knowledge about electromagnetism and wave propagation through interactive simulations and visualizations. Users can change various parameters and observe the experiment outcomes depending on the changes. Field visualizations and wave representations make invisible phenomena visible and give students a better understanding of the underlying physical concepts.

In order to evaluate the impact of virtual reality on immersion, an A/B split user study with 20 participants was conducted. The goal of this study was to compare the two variants of Maroon (Maroon PC and Maroon VR) to identify the advantages, disadvantages, and application scenarios. The results of the study show that such an interactive and immersive learning environment has a high potential to improve guided learning in classes and self-directed learning at home by making the learning content more interesting and understandable.

Kurzfassung

Unsere heutige Welt ist geprägt durch schnelle Veränderungen und neuen Technologien, die unsere Leben beeinflussen. Fähigkeiten in Naturwissenschaften, Technik, Ingenieurwesen und Mathematik sind heutzutage immer gefragter. Daher ist es eine Notwendigkeit die Ausbildung in diesen Bereichen zu verbessern. Oft reichen theoretische Kenntnisse und Formeln nicht aus, um komplexe physikalische Phänomene, wie Magnetismus, Induktion oder Wellenausbreitung zu verstehen. Simulationen sind eine gute Möglichkeit, physikalische Gesetze zu visualisieren und dadurch ein besseres Verständnis ihrer Funktionsweise zu vermitteln, indem sie den Benutzer durch Interaktionen mit der virtuellen Welt direkt in den Lernprozess involvieren. Dieser Ansatz des aktiven Lernens hat sich als effektive Lernmethode gegenüber traditionellen Methoden erwiesen. Durch den Einsatz von neuen Technologien kann auf die Bedürfnisse der digitalen Generation eingegangen werden, die es gewohnt ist Informationen sehr schnell zu empfangen und direkten Zugriff auf Informationen zu haben. So setzen aktuelle Lernmethoden bereits vermehrt auf Informations- und Kommunikationstechniken, um Wissen zu vermitteln. Virtuelle Erfahrungen ermöglichen relative Grenzen des individuellen Potenzials zu überwinden, die durch die persönliche Vorstellungskraft gegeben sind. Während virtuelle Welten simulierte Orte sind, die besucht werden können, eröffnet die virtuelle Realität eine immersive Möglichkeit virtuelle Welten zu erkunden. Ein wesentlicher Faktor beim Lernen mit Simulationen und virtuellen Welten ist die ständige Interaktion mit den Lernmaterialien. Virtual Reality Technologien ermöglichen die Interaktion mit der virtuellen Umgebung und erreicht eine hohe Intensität der Immersion. Dies bietet ein großes Potential ansprechende und motivierende Lernerfahrungen zu entwickeln.

In dieser Arbeit wird das Design und das konzeptuelle Model des immersiven Physiklabors Maroon und die in dieses Framework integrierten Experimente vorgestellt. Maroon ist als interaktive, erweiterbare, virtuelle Laborumgebung konzipiert und ermöglicht die Erstellung verschiedener Lernmodule, dessen Inhalte in Lernstationen geladen werden. Die Lernumgebung unterstützt dabei verschiedene Technologien mit unterschiedlichen Interaktion-, Engagement- und Immersion-Level. Die Room-Scale VR Variante ist eine spezielle Erweiterung mit immersiven Elementen, die die Aufmerksamkeit auf den Lerninhalt lenken soll. Die entwickelten Experimente sollen so Lernenden durch interaktive Simulationen und Visualisierungen physikalische Wissen über Elektromagnetismus und Wellenausbreitung vermitteln. Benutzer können verschiedene Parameter der Experimente verändern und so den Einfluss auf den Experimentausgang beobachten. Durch Feldvisualisierungen und Wellendarstellungen werden unsichtbare Phänomene sichtbar und fördern dadurch ein besseres Verständnis der zugrundeliegenden physikalischen Konzepte.

Um den Effekt der Immersion mit Virtual Reality zu untersuchen, wurde eine A/B Split User Studie mit 20 Teilnehmer durchgeführt. Das Ziel war es, die beiden Varianten PC und VR zu vergleichen und die Vor- und Nachteile sowie Anwendungsszenarien zu identifizieren. Die Ergebnisse der Studie zeigen, dass eine interaktive und immersive Lernumgebung, wie Maroon, großes Potenzial hat, um begleitetes Lernen in der Schule und selbstgesteuertes Lernen zu Hause zu verbessern indem es den Lerninhalt interessanter und verständlicher darstellt.

Acknowledgements

At this point, I would like to thank all those who supported and motivated me during this thesis.

First of all, I would like to thank my supervisors Christian Gütl and Johanna Pirker for their helpful suggestions and constructive feedback. Without their constant support and guidance, this work would not be possible.

Special thanks go to Gernot Rahm who helped me in designing the 3D models for the experiments. Without his professional assistance, the experiments would not look like today.

Further, I would like to extend my thanks to all participants for agreeing to be part of the evaluation. My thanks go to their willingness to give feedback, contributions, and answers to my questions.

I would also like to thank my colleagues Philipp Hafner, Lukas Schabler, and Michael Schiller for their great support during my studies and this work. Their numerous inviting comments and suggestions helped me in creating this thesis.

Furthermore, I would like to extend my thanks to Philipp Hafner for proofreading this thesis.

Finally, I would like to thank my family and friends, who made my studies possible through their unwavering support.

Contents

1. Introduction

Teaching and learning about science, technology, engineering, and mathematics (STEM) is challenging and demanding. Knowledge in these disciplines is increasingly in demand. The deficit of graduates in these areas is a significant problem. Olson and Riordan (2012) reported that the number of students with a degree in STEM fields needs to be increased. One issue is the students' lack of interest and enthusiasm. For many students, STEM fields are boring, hard, and complicated. Traditional learning methods make it difficult to impart problem-solving competence conceptual understanding. Learning tools with interactive and engaging activities can help students to gain a better understanding of concepts and phenomena. Freeman et al., 2014 showed that active learning is an efficient way to improve students performance. Information and Communication Technologies supports students in self-directed learning, active learning and group-based learning. Tools like interactive simulations, visualizations, virtual and remote labs, as well as playful learning use the active learning approach to involve students directly in the learning process. They learn by doing and thinking about what they are doing. The Technology-Enhanced Active Learning (TEAL) concept combines lectures, simulations, and hands-on desktop experiments to form a collaborative learning experience. Simulations allows students to be part of the simulated environment where they can interact with the virtual scene. They allow students to learn complex concepts in a simpler and safer environment. Virtual laboratories combines simulations and visualizations in a lab-like environment with a similar experience compared to traditional hand-on laboratories. Integrating playful elements into simulations make the learning experience more engaging and increases the learning outcomes. Through Virtual Reality (VR) technologies, a more immerse and engaging feeling can be achieved. The users feel more immersed by interacting with the environment as a part of the virtual world. In combination with virtual laboratories, user are fully engaged in the virtual environment and have to handle situations in a realistic way.

1.1. Goals and Motivation

Due to the lack of students' interest in STEM disciplines, a more interactive and engaging teaching model is needed to overcome students' discontent. In order to develop such a model, the virtual physics laboratory Maroon[1] is taken as a starting point. It is an interactive three-dimensional experiment environment designed for active learning in the classroom or at home. Maroon uses different technologies such as virtual reality devices, mobile technologies, or web-based applications to obtain different levels of engagement and immersion. Experiments and learning activities are organized as learning stations which can be easily extended by further learning contents. Since there are currently only two learning activities and two electrostatic experiments, the lab should be extended by further experiments.

The main objectives of this thesis are the design, development and evaluation of new physics experiments for the virtual laboratory Maroon. The goal is to create a laboratory environment with a variety of interactive experiments and learning experiences for VR and PC. Furthermore, the VR experience and the graphical user interface for the desktop application should be improved to make it more interesting and easier to use. The development includes the following experiments:

- Falling Coil: Shows the dynamics of a conductive non-magnetic ring falling on the axis of a fixed magnet.
- Faraday's Law: Shows the interaction between a magnet and a coil constrained on the horizontal axis.
- Capacitor: Shows the storage of energy in an electric field.
- Huygens Principle: Shows the physical model of diffraction.

The experiments should increase the students motivation and enthusiasm in physics. The main goal is to make physical phenomena understandable for everyone.

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[1] https://jpirker.com/maroon/

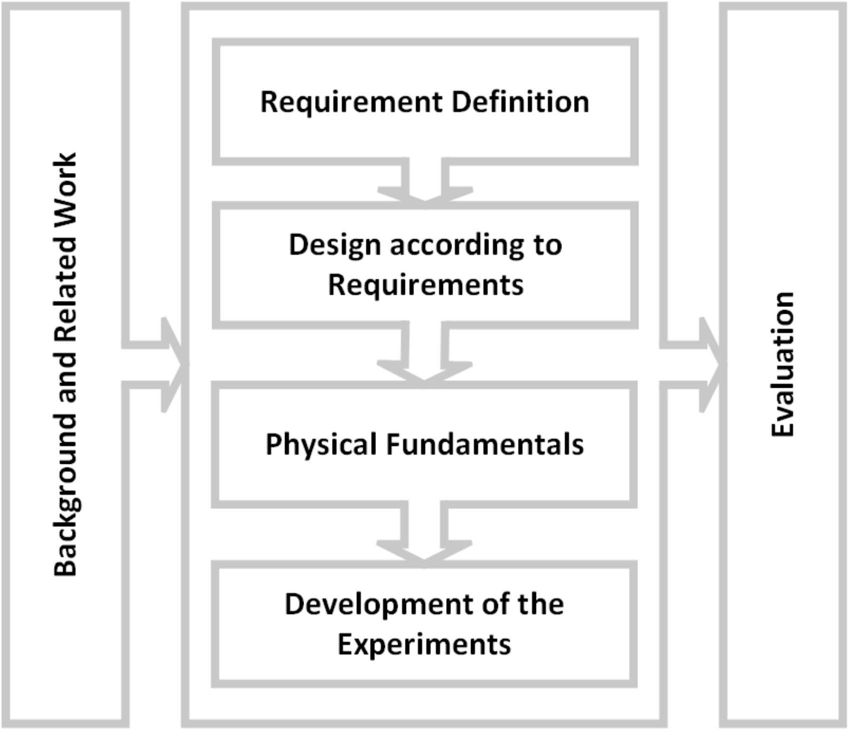

Figure 1.1.: The structure of this thesis

1.2. Methodology and Structure

This thesis is structured into three main parts. The first part focuses on the background and related work (Chapter 2). The second part describes the system requirements and the design (Chapter 3), the physical fundamentals (Chapter 4), and the development of the experiments according to the system requirements (Chapter 5). The third part discusses the evaluation results of the implemented system and experiments. Figure 1.1 gives a structural overview of this thesis.

Chapter 2 gives an overview of the theoretical background and the related work regarding STEM education, virtual and playful learning in physics, and VR experiences in education. After a short explanation of STEM and the necessity of more graduates in these fields, traditional learning methods and their disadvantages are described. Afterwards, the advantages of interactive teaching and learning techniques such as simulations, visualizations, virtual laboratories are discussed and game-based learning models and collaborative learning environments are outlined. In this context, the usage of VR technologies to increase the feeling of immersion and engagement is discussed.

Chapter 3 defines the user target group and their requirements to customize the system according to their needs. It specifies the functional and non-functional system requirements and describes the conceptual structure of the laboratory environment. Furthermore, it introduce the conceptual design of the experiments and simulation implemented in Maroon.

Chapter 4 focus on the physical fundamentals which are necessary for the development of the experiments. It describes the physical concepts of the electric and magnetic field as well as the Huygens principle and defines all relevant formulas for modelling a physically-correct world.

Chapter 5 describes the development details of the physical components and the visualizations of the implemented experiments. After a short overview of the experiment architecture and the specific control elements, the interface of an electromagnetic field and the electromagnetic objects are introduced. Furthermore, the implementation of the wave propagation, as well as the interference of multiple waves is described. Afterwards, the different visualizations used to illustrate the underlying physical phenomena are described.

Chapter 6 analyses the results of the system evaluation. It describes the used materials and hardware components as well as the method and procedure during the evaluation. Afterwards, the participants are described and the results of the questionnaires are discussed. The chapter focuses on the research objectives: engagement, immersion, learning experience, experience, and user experience.

Chapter 7 explores problems that occurred during the design and the development phase. The following chapter gives some ideas for future improvements and developments. The last chapter summarize the research outcomes and their impacts.

2. Background and Related Work

Rapid changes are shaping our world. New technologies are influencing more and more areas of our lives. The digitization progress is accelerating this evolution. Technological progress is changing the demands on young people. Skills in the disciplines of science, technology, engineering and mathematics are more in demand and invest versatile professional and personal prospects (Olson & Riordan, 2012). The students lack of interest and enthusiasm is one of the reasons for high failure rates in these fields. For many students, it is not clear why they have to learn certain contents in mathematics and natural sciences. However, this is an essential prerequisite for the evolvement of a persistent learning motivation (Reeve, Jang, Carrell, Jeon, & Barch, 2004).

This chapter discusses different tools and approaches in order to preserve and expand interest and passion for science and technology of the new generation.

2.1. STEM Education

Many people associate science with physics and chemistry. But what is science? Science is trying to give correct answers for questions which we feel like having the correct answers to. Understanding the nature of science enables clear ideas of how science can be used in policy making. A valid scientific basis allows useful public funding projects (Chalmers, 2013). Especially for industrially developed countries, great potential exists for maintaining their living standards and prosperity through innovations (Milbergs, 2004). The term STEM refers to teaching and learning in the fields of science, technology, engineering, and mathematics. STEM topics are becoming more and more relevant and is a significant driver of innovation. Therefore, STEM is a necessity to enhance the preparation of our next generation of citizens (Zeidler, 2016).

Expository instructions, self-directed learning, and hands-on experiments are common learning methods in physics education (Lee, Guo, & Ho, 2008). While expository instructions are one-way communication, where information is transferred from the source to the students (Riza & Sevrika, 2015), interactive experiences and hands-on experiments increase student's motivation and performance (Olson & Riordan, 2012). A central approach to improve STEM education is to create a framework for improving the quality of STEM teaching. Innovative teaching and learning environments should increase positive emotions and professional competence (Zeidler, 2016). The next sections consider traditional and different interactive learning methods in education.

2.1.1. Traditional Learning

In classes, memorization of descriptions and explanations dominate learning forms. Traditional learning methods ignore active and independent thinking. Traditionally, they usually use lectures and hands-on laboratories to impart knowledge. Generally, lecturers present their learning stuff based on textbooks, while students listen to the lecturer and are not actively involved (Hake, 1998). The lecturers often just convey solutions to problems without actually explaining how to solve them (Freedman, 1996). Facts, principles or procedures learned without explanations result in poor understanding (Rittle-Johnson & Alibali, 1999). Many students think that the topics they learn are not related and their class learning has nothing to do with real life (Perkins & Simmons, 1988). For students, it is challenging to use their learned skills and knowledge in out-of-class situations if materials are context-bound or presented in abstract forms (Anderson, Reder, & Simon, 1996).

As the philosopher, Confucius (551 BC to 479 BC) said: *"I hear and I forget. I see and I remember. I do and I understand"*, hands-on experiences are essential for learning. Field trips with special visits under educational guidance and objectives help students to explore what is to be learned. The personal confrontation enables deep and holistic impressions and thus facilitates access to phenomena and topics. Through their own interaction, observation and manipulation, students can see and understand elements through their own eyes. Furthermore, field trips provide entertainment that increases student motivation. It increases the initiative, the effort and endurance during the task and improves the cognitive processability as well as overall performance. Typically, excursions in the field of natural sciences have destinations such as an observatory, a natural park, a show mine or the exploration of geological forms and special laboratories (Nir, 1993). Learning by doing is a proven concept that is applied in many areas (Bruner, 1990). In the fields of science, technology, and engineering it is essential to gain knowledge through practical experiences. Therefore, laboratories have a central and distinctive role in science education. Students gain an understanding of scientific concepts, skills in scientific research and perceptions (Hofstein & Lunetta, 2004).

2.1.2. Active Learning

Active learning is a successful teaching method where students are directly involved in the learning process. It typically includes educational activities which involve students in doing things and thinking about what they are doing. This has been shown to be an effective strategy for increasing the students' performance compared to traditional methods (Bonde et al., 2014; Olson & Riordan, 2012).

Freeman et al. (2014) have shown how efficient active learning can be compared to traditional learning. Her research includes the quantitative and statistical processing of 225 study results. The results show an improvement in performance with active learning and an increased ratio for failure with traditional learning. The probability of falling a traditional course was 1.5 times higher than in an active learning course. The mean failure rate under active learning were 21.8% and under traditional learning 33.8%. Heterogeneity analyses showed no statistically significant differences between the STEM disciplines. The effect of active learning occurs in all class sizes. The most significant impact was achieved with a maximum class size of 50 participants.

There are several interactive teaching and learning strategies with which the effect of active learning can be achieved by applying teaching material to real situations or problems on a practical level. Interactive simulations, visualizations, virtual or remote laboratories, as well as gamified learning environments are tools that can be used to support teaching and enhance engagement, immersion, and motivation (Bonde et al., 2014). User interfaces are becoming more intuitive to meet the needs of the individual learner and to provide more personalized learning and greater learner autonomy. De Freitas and Neumann (2009) explores changes in teaching by considering an explorative learning model that allows practitioners to rethink their teaching methods in 3D and immersive space where learning sequences and experiences are choreographed to support peer interactions and exchanges. Teaching focuses on sequencing learning experiences, meta-reflection, peer assessment, and group work. The physics learning tool "Technology Enabled Active Learning" (TEAL) is a special type of active learning. It was developed at the Massachusetts Institute of Technology (MIT) to teach students physical concepts in an interactive and engaging form. TEAL focuses on collaborative and interactive learning using three-dimensional simulations and visualizations as well as hands-on experiments. Simulations and visualizations can be projected onto project screens around a specially designed classroom. The idea of these classrooms is to merge lectures recitations and hands-on experiments into one common experience. Students work in small groups on desktop experiments and use the TEAL software for simulations and visualizations. Group discussions and collaborative assignments give a deeper understanding of the taught concepts (Dori & Belcher, 2005). Introductory electromagnetism courses at MIT already have been using TEAL since 2000. Students who used TEAL in class gained significantly better conceptual skills than those who used traditional teaching methods. Furthermore, a long-term study showed a continuing effect of TEAL courses on the retention of physical concepts (Dori, Hult, Breslow, & Belcher, 2007). The only limitation of this approach is, that it requires an interactive and collaborative setting. Providing special classrooms for TEAL is extremely expensive (MIT, 2005). Technology-enhanced learning methods help to overcome these drawbacks. The following section discusses how it can be used to support the new learning generation.

2.1.3. Technology-Enhanced Learning

To reach the new generation, it is necessary to respond to their needs. The Internet, computer games, smartphones and instant messaging are essential parts of their lives. This modern equipment and the extensive interaction with it led to different patterns of thinking and to a fundamental difference in processing information. Digital natives are used to receiving information very fast, have a desire for multitasking and love direct access to information. They prefer learning through activities in contrast to reading or listening and have a preference for mixing work and play (Thompson, 2015). Information and Communication Technologies (ICT) and media are an integral part of current learning methods. Teachers use media as a teaching aid while students use it to support their learning, for example by using learning management systems such as Moodle[1]. It is not a matter of understanding media and ICT as isolated from the learning process, but rather of combining these interdisciplinary concepts into teachings as an essential element (Harandi, 2015). Horton (2011) distinguished between standalone courses, learning games and simulations, mobile learning, social learning, and virtual-classroom courses. Interactive exercises and practical activities such as remote laboratories and simulations increase the student's participation.

Currently, universities usually use traditional hands-on laboratories to teach students practical knowledge with real equipment. However, handling many students is quite a problem for universities. There are currently two approaches for mastering this challenge: virtual and remote labs (Ma & Nickerson, 2006). While in virtual laboratories the entire laboratory environment is realized in software, remote laboratories make it possible to use devices from a remote point. Even complex systems such as robots, control devices or process instruments can be monitored, operated and programmed remotely in real time. The test procedures can be viewed on the computer via live cameras and generated measurement data can

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[1] https://moodle.com

be download. The server operates as a web publisher, lab scheduler and database manager. The user gives remote instructions that are received and executed by the workstations. The laboratory devices are controlled by the workstations and monitored in real-time. This allows a worldwide exchange of resources and laboratories (Chen, Song, & Zhang, 2010).

In a large-scale study with 306 participants, Corter et al. (2007) compared simulated (virtual) laboratories, remote laboratories, and hands-on laboratories. The authors evaluated students learning outcomes and preferences for several laboratory formats in engineering courses. After each laboratory lesson, the students' performance was measured via a multiple-choice test. The learning outcomes in virtual and remote laboratories were higher or as high than in traditional hands-on laboratories. Many students saw a benefit in technology-enabled laboratory formats but preferred the hands-on work in physical laboratories because it was easier for them to work in teams. However, virtual and remote laboratories were rated as the more comfortable and reliable solution. Lindsay and Good (2005) analyzed the effects of the separation from physical hardware in laboratory classes on student's learning outcomes. The belief that somewhere hardware was present leads to different perceptions. Based on these perceptions, different setups lead to different learning outcomes. While students in remote laboratory setups focused on applying the learned theory, students who used simulations focused on learning during the class. It has been shown that methods such as self-directed learning, active learning, and group-based learning as well as motivational aspects are becoming increasingly important in STEM education. By creating a goal-oriented learning environment with practical uses of principles and theory, students gain a deeper understanding (Bell, 2016). The next section will focus on different collaborative, motivating and interactive virtual learning methods in physics.

2.2. Virtual and Playful Education in Physics

Images are the language of human thought. As Albert Einstein said: *"I am enough of an artist to draw freely upon my imagination. Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world"*

(Viereck, 1929). Einstein already used visual illustrations with the power of his imagination to develop his ideas, views, and theories. According to the Oxford Dictionary (2019), imagination is “the faculty or action of forming new ideas, or images or concepts of external objects not present to the senses.” Warnock (1976) suggests, that imagination is necessary so that we can recognize things in the world as familiar. Imagination and memory are central elements of life and present relative limits to individual potential. Thanks to virtual experiences, it is feasible to exceed these limits (Vincelli, 1999). Virtual environments are becoming increasingly important in the context of learning and knowledge acquisition. They are simulated interactive models of reality by computer technologies. Users interact with the environment and can change the system behavior. One of the advantages of the use of virtual environments in education is the possibilities of illustration (Weller, 2007). The following sections describe how to illustrate physical phenomena using simulations and visualizations and how to implement such technologies in virtual and playful environments.

2.2.1. Simulations and Visualizations

Quite often, theoretical knowledge and formulas are not enough to comprehend complex processes and phenomena. Simulations are a good way to visualize physical laws and help in gaining a better understanding of how they work by allowing a user to interact with a predefined scene. A simulation invites students to play a role in a simulated environment in order to learn skills that can be transferred to real life. Students make decisions and learn from successes and failures. Simulations make it possible to learn complex concepts or skills in a simpler and safer environment (Lunce, 2006).

Research shows, that traditional learning methods are often inefficient and lead to misunderstandings among students. For example, students often mistake position, speed and acceleration of a moving object and therefore mix theories (Halloun & Hestenes, 1985) or are not able to clearly distinguish between voltage, current, energy and power (McDermott & Shaffer, 1992). Simulations should help students to overcome these misunderstandings. Jimoyiannis and Komis (2001) used the virtual physics laboratory ”Interactive

Physics"[2] to teach the fundamental principles of Newtonian mechanics and to analyze the effects of simulations on students. Their outcomes show that the simulations improved student performance and help them to overcome their cognitive constraints.

In addition to classical mechanics, simulations can be used in different areas of physics, including areas that cannot be perceived by human senses. The Technology-Enabled Active Learning (TEAL) Project at the Massachusetts Institute of Technology uses simulations and visualizations to teach students electromagnetic phenomena and processes. Figure 2.1 shows a simulation of the Falling Coil experiment. By displaying field lines, vector arrows or iron filings, the invisible phenomena become visible and students gain a better idea of the complex concepts. In a study, students were asked about their knowledge of electromagnetism before and after the exercises. The results showed a significantly higher performance among students using the simulations (Dori & Belcher, 2005).

There already exists a wide variety of simulations in STEM disciplines. The Physics Education Technology (PhET) Project[3] offers a large number of interactive simulations in an intuitive, game-like environment. Most of the simulation can be executed without installation through a regular Web browser. The use of these ready-made simulations requires less preparation time and are highly efficient. Traditional hands-on laboratories contain a lot of information that cannot be collected by students. The additional information leads to confusion and intellectual load. The student's attention is often focused on things that the instructor considers as irrelevant. A well-designed simulation establishes the connection to the real world and focuses the student's attention on essential information (Wieman & Perkins, 2008). The next section shows how we can combine the power of simulations and visualizations within laboratory environments in an interesting and engaging manner.

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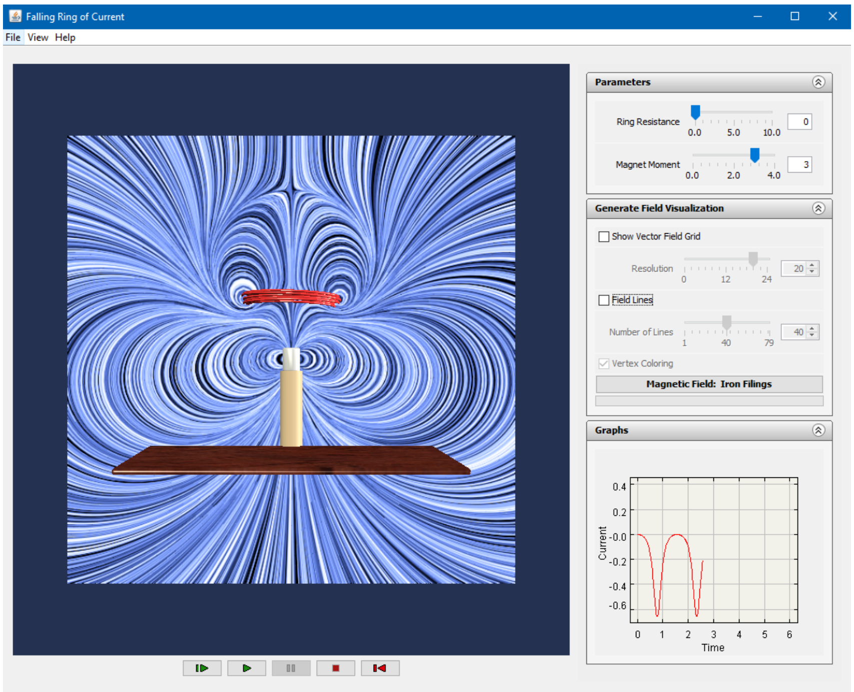
[2] http://www.design-simulation.com/IP/index.php

[3] https://phet.colorado.edu/



Ring Resistance 0.0 5.0 10.0 0

Magnet Moment 0.0 2.0 4.0 3

☐ Show Vector Field Grid

Resolution 20

☐ Field Lines

Number of Lines 40

☑ Vertex Coloring

Figure 2.1.: Falling Coil Simulation in TEALsim

2.2.2. Virtual Laboratories

A virtual laboratory is a simulation-based, multimedia model of a real laboratory in the form of a teaching and learning system. Virtual laboratories are a cost-effective way for schools and universities to provide laboratory environments (De Jong, Linn, & Zacharia, 2013). They are highly flexible in creating virtual experiments and make complex setups unnecessary. Students can experiment at the same time and adjust system parameters that are difficult or even impossible to change in real situations. By combining different visualizations, unseen scenes become visible, which gives students more clarity about the concepts to be learned. In addition to these advantages of virtual laboratories, there are also some problems and drawbacks inherent to this approach. Dynamic modeling of objects may be complex and time-consuming, which requires appropriate computer resources. Due to the fact that the system itself is not real, students may not take the system seriously and see it as a game. Only real experience makes students more serious, responsible, and careful (Potkonjak et al., 2016).

Combinations of physical and virtual experiments can make use of the features of each approach. Aşıksoy and İşlek (2017) analyzed the impact of virtual laboratories versus real laboratories. The results show that the virtual laboratory had a similar positive impact on students. Additionally, the students gave overall positive feedback on their experience with the virtual environment. An additional study with chemistry students confirms these results. Tuysuz (2010) used 16 virtual experiments to evaluate the learning effect of virtual laboratories in chemistry. The student's attitude towards chemistry has changed positively and their performance has increased. In an additional review, De Jong et al. (2013) analyzed the similarities and differences between physical and virtual laboratories. The authors came to the conclusion that any laboratory form has it owns advantages for certain use cases. Physical laboratories are more suitable to acquire practical laboratory experience and to interact with the real world. Virtual laboratories enable expandable experiments, multiple access and the visibility of unseen phenomena. Zacharia, Olympiou, and Papaevripidou (2008) showed that experimenting with the combination of physical hands-on laboratories and virtual laboratories enhanced students' conceptual understanding more than experimenting with physical laboratories alone.

The rapid development of the internet in the last few years has helped to design high quality virtual and remote laboratories. There is a huge number of development tools that can be used to build modern virtual lab environments (Chen et al., 2010). Several virtual and remote laboratories were already implemented with Java (Chen, Olowokere, & Graham, 2008; Röhrig & Jochheim, 2000). The release of Web 2.0 opened new possibilities to develop more modern virtual and remote lab environments (Lopez-de-Ipina, Garcia-Zubia, & Orduna, 2006). Furthermore, Potkonjak et al. (2016) believe that the continuous technological progress in computer graphics, virtual reality, and virtual world leads to a rapidly expanding of virtual technologies. In addition to the technical part, the pedagogical aspect is essential as well. Unfortunately, most simulations focus primarily on the imitation of physical phenomena and not on enhancing student's learning outcomes (Mislevy, 2013). An essential prerequisite of successful learning is motivation. Ways to enhance motivation are playful learning, collaborative learning, and immersive experiences. The next section focuses on digital game-based learning to increase motivation an engagement in STEM education.

2.2.3. Digital Game-based Learning

Using appropriate and tested teaching practices, it is still a challenge to maximize the fun of learning and to motivate students to learn. Therefore, it requires learning methods that are as informative as they are fun. For that, the pleasure of playing can be used to make learning methods more attractive and engaging. Playful learning is in the nature of human beings. It is an archetypal activity that comes from biological structures and enables learning through trial and error (Brown & Vaughan, 2010). Children train their intellectual abilities by exploring the environment in a playful way. They learn physical laws and how to handle objects. For example, they expand their spatial perception and their knowledge of mechanical laws by constructing objects with building blocks. According to Piaget (1973), stimulating interest, initiative, experimentation, discovery, play, and imagination are fundamental to the development of a child's ability to learn. In the last few decades, significant investments have been made in the integration of games in the field of education, either in the form of playful learning or serious gaming (Pavlidis, 2015).

Learners often feel left alone and unsupported. Game-based learning uses the learning and motivation potential of digital games to acquire real knowledge. The use of game-based learning is intended to create opportunities which conventional learning methods do not offer (Hamari et al., 2016). The use of games or game-design elements in educational environments has shown to be useful to increase learner's motivation and engagement, especially in the field of STEM. Several studies found that the use of games is more effective than traditional classroom instructions to improve students performance (Randel, Morris, Wetzel, & Whitehill, 1992). Pirker and Gütl (2015) developed a framework for gamification of simulation in the fields of STEM. They designed a gamification model adapted to the properties of STEM educational approaches with a focus on scientific simulations. The concept shows that game techniques can enhance simulations and produce a more engaging and motivating experience. Bonde et al. (2014) developed a realistic, immersive, and playful version of a virtual laboratory in the field of biotech education including ten gamified simulations. They tested a crime-scene lab and a genetic engineering lab where students explore a crime scene by analyzing blood samples or produce medicine and test it on virtual mouses. Their study shows a 76% increase in learning outcomes compared to traditional teaching and a 101% increase when used it in combination. The result indicates that gamified laboratories are an attractive way to improve student's engagement and motivation. Additionally, the design of educational environments can not only be enhanced by game elements. Collaboration, immersion, presence and flow are motivational drivers too. The next two sections introduce virtual worlds and techniques that can be used to learn more immersively and collaboratively.

2.2.4. Collaborative Learning

Collaborative learning is a situation where two or more people learn together. In contrast to individual learning, participants in collaborative learning benefit from each other's resources and skills (Dillenbourg, 1999). There are many powerful tools that support collaborative learning activities and tasks. Virtual worlds are such instruments to support collaborative learning. They are simulated environments implemented by a computer. A primary characteristic is the simultaneous participation of several users who can move independently in the virtual space. Each visitor is represented by an avatar and can communicate with others (Bartle, 2004). Virtual worlds are made and designed through their use. Through communication and social interaction, virtual worlds are an ideal platform for the engagement of learners in educational practice (Moschini, 2010). Ibáñez et al. (2011) focused on engaging learning experiences to improve communication skills within a virtual 3d multi-user world. They developed a collaborative learning environment where students will train communication skills under the constructive principles of situated learning and cooperative/collaborative learning. Gütl (2011) describe virtual worlds as an opportunity to mitigate or even overcome the problems of existing technologies in the context of collaboration. The results of two studies of collaborative learning in virtual worlds show that such environments are a promising alternative to meeting more easily and spontaneously. Furthermore, they show that an integrated platform with a collection of tools and multiple communication channels provides both real and different phenomena of the real world. A well-designed environment provides subtle clues and bits of evidence that give students the possibility to practice skills in inductive thinking. Virtual worlds support a wide variety of media based on image, action, and sound. That promotes different learning styles and stimulate students to use their observational skills related to their senses (Trotta & Glenn, 2012). Popular extensible, collaborative virtual world environments are "Second Life"[4], "OpenSimulator"[5] and "Open Wonderland"[6]. They are used as a platform for education by many institutions.

Many educational institutes are already practicing virtual worlds or interactive game-based scenarios in the field of STEM. An open, immersive and visual 3D platform combined with the simple creation of content makes it valuable for research. Lang and Bradley (2009) used the Second Life platform to develop an interactive and collaborative visualization of data from molecules and proteins to spectra and experimental data. They demon-

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[4] https://secondlife.com/

[5] http://opensimulator.org

[6] http://openwonderland.org/

Figure 2.2.: Overview of the Virtual TEAL World for Faraday's Law (Pirker, Berger, Guetl, Belcher, & Bailey, 2012).

strated how these visualizations can be scripted for immersive educational activities and real-life collaborative research.

Another example of an interactive virtual world is the "Virtual TEAL World" (VTW) developed by Pirker (2013). It is a flexible virtual and three-dimensional learning environment that integrates the educational components and scenarios of the TEAL model. Existing tools, experiments, videos, and simulations were implemented for the virtual world's framework "Open Wonderland" in order to imitate the existing TEAL environment. The used framework is fully extensible, which allows developers and graphic artists to create new worlds easily or add features to existing worlds. The purpose of VTW is to provide a virtual learning environment that achieves learning outcomes as good as the real TEAL environment. The focus is on enabling discussions, active participation and collaboration. Figure 2.2 shows the VTW environment where different parts cover different approaches of TEAL (Pirker, Berger, Guetl, Belcher, & Bailey, 2012).

While virtual worlds are simulated places that can be visited, virtual reality opens up an immersive way to explore virtual worlds. The next section discusses different virtual reality technologies and how they can be used in educational scenarios.

2.3. Virtual Reality in Education

In order to obtain a more immersive and engaging feeling, the potential of Virtual Reality (VR) technologies can be used to develop engaging learning experiences. An advantage in the use of three-dimensional virtual worlds is the positive effect of immersion in learning processes. VR provides interaction with the virtual environment, achieving a much higher intensity of immersion. This immersion, engagement or even flow is an essential factor in developing interactive and involving experiences. Csikszentmihalyi and Csikszentmihalyi (1992) demonstrated in theoretical and empirical studies of flow experience an optimal state of consciousness that improves the mental state of a person. They considered how the ability to experience flow influences work-satisfaction, academic success, and overall quality of life and present different characteristics of flow experiences.

Immersion effects are related to flow. It describes the personal feeling of "Sense-of-being-there". Concerning virtual reality, immersion is determined by the level of representation and presence. The presence experience of learners in three-dimensional environments is associated with the perception of their virtual presence (Davis, Murphy, Owens, Khazanchi, & Zigurs, 2009). Modern VR technologies support different immersion levels using room-scale VR or head-mounted VR devices. Depending on the VR environment, the perception of the activities and the emotions can be varied. This makes it essential to look at different design concepts for each VR environment. Settgast, Pirker, Lontschar, Maggale, and Gütl (2016) evaluated various VR scenarios in regards to immersion, engagement, cyber sickness, and the overall experience.

A primary factor in learning with simulations and virtual worlds is the constant interaction with the learning material, subjects, contents, and contexts. Burdea and Coiffet (2003) describes imagination, immersion, and interaction as the "three I's" of learning with virtual realities. VR has proved to be a useful tool in primary, secondary and even in higher education (Merchant, Goetz, Cifuentes, Keeney-Kennicutt, & Davis, 2014). It allows a direct feeling of things and phenomena, supports practice in a safe environment avoiding possible real dangers. Game-based elements increases the learner's engagement and motivation while extending the spectrum of supported learning methods (Freina & Ott, 2015). Virtual Reality covers a wide range of applications. There are already applications in the areas of medical sciences (Górski, Buń, Wichniarek, Zawadzki, & Hamrol, 2017), therapy (Lindner et al., 2017), architecture (Portman, Natapov, & Fisher-Gewirtzman, 2015), and manufacturing (Choi, Jung, & Noh, 2015). Developing an immersive, simulated three-dimensional environment requires special software and hardware. The next sections describe different virtual reality devices and how such tools are used to build more interactive and engaging laboratory environments.

2.3.1. Virtual Reality Devices

Obtaining an immersion feeling requires special VR devices such as the Oculus Rift[7], HTC Vive[8], Sony Playstation VR[9], or the CAVE[10]. The CAVE (Cave Automatic Virtual Environment) represents a three-dimensional virtual room where projectors illustrate the virtual world on walls, floors, and ceilings. An alternative way is the use of head-mounted displays (HMDs). They create a spatial impression by rendering two images and displaying them from different perspectives. Figure 2.3 illustrates the view gained through virtual reality glasses. The frequency and the resolution are important factors for visual quality. Lin, Duh, Parker, Abi-Rached, and Furness (2002) analyzed the effect of field-of-view in a virtual environment on presence, enjoyment, memory, and simulator sickness. They found, that the factors varied depending on the display field-of-view. Both, hardware for projection and interaction, need to be used to produce a full immersion (Górski et al., 2017). Specially designed input devices allow interaction with the virtual environment. Computing and graphics-intensive applications require a powerful computer or game console to prevent long latencies. Finally, hardware together with Software forms a VR system.

Figure 2.4 shows a classic Virtual Reality room-scale setup. The two base stations emit laser beams that are detected by photo-sensors on the headset

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[7] https://www.oculus.com/rift/

[8] https://www.vive.com/eu/

[9] https://www.playstation.com/en-us/explore/playstation-vr/

[10] https://www.evl.uic.edu/pape/CAVE/

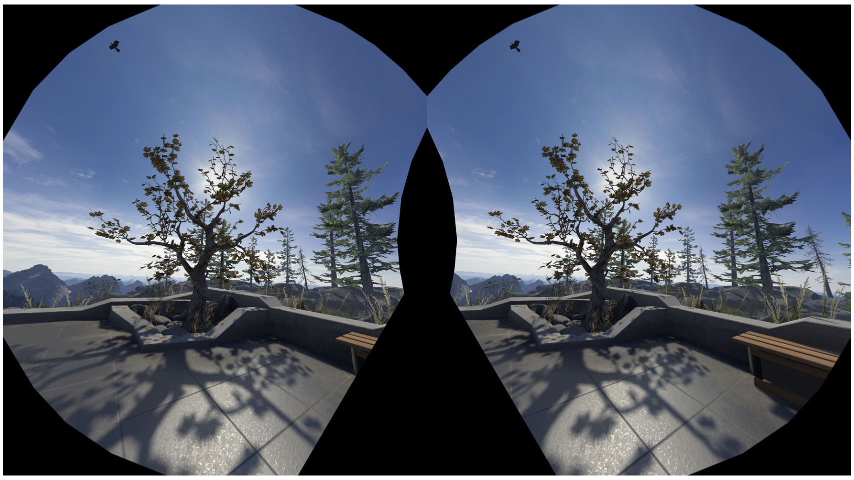

Figure 2.3.: View through a Virtual Reality Headset[13]

and the controllers. Based on the time difference between the impact of the laser beams on the sensors, the computer can calculate the exact position and orientation of the device. The controllers are specially designed for VR and allow interactions with the virtual world. They include a multifunctional trackpad, programmable buttons, a two-stage trigger, and a haptic feedback function for improved user interactions (HTC, 2019). Furthermore, there are also specific mounting devices with lenses for smartphones which provide a more portable, flexible and lightweight way of experiencing virtual reality. The device has to be equipped with adequate sensors and the required performance. The Samsung Gear VR headset[11] or the Google Cardboard[12] are well-known mobile VR solutions. These mobile VR devices are a cheap, attractive alternative for schools that do not have the resources to buy expensive equipment (Olmos, Cavalcanti, Soler, Contero, & Alcañiz, 2018).

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[11] https://www.samsung.com/global/galaxy/gear-vr/

[12] https://vr.google.com/cardboard/

[13] Screenshot from Steam VR Home

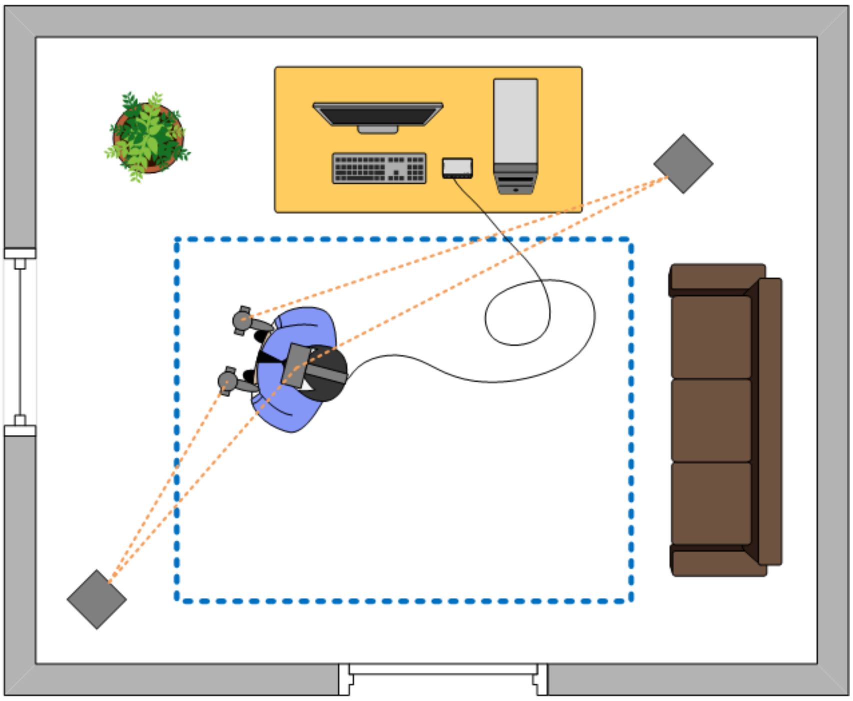

Figure 2.4.: Virtual Reality Room Setup

2.3.2. VR Experiences in Education

Psychology describes “Embodied Cognition” as an interaction between body and mind. An action (e.g. interaction with the virtual world) triggers a response in the human brain (Wilson & Foglia, 2017). These reactions can be triggered much more by VR than by classical lectures or conventional e-learning. Virtual laboratories in combination with VR tools give an even more immersive experience. Users are fully immersed in the virtual environment and must handle the situations in a realistic way. Entering the virtual world reduces any distraction caused by external influences. Nowadays, there are several VR laboratories developed and used for training and education scenarios. Educational institutions and companies realized the benefit of integrating VR technologies. NASA successfully uses a VR laboratory for astronaut training. They use elements of physical reality together with virtual reality technology to improve astronaut performance. Astronauts work with 3d printing plastic replicas of tools. By wearing a VR headset, they see a photo-realistic representation of the used tool that’s tracked one-to-one in 3d space. The substitute tools reduce the cost of necessary training while still maintaining fidelity (Delgado & Noyes, 2017). The replica of real laboratories in VR can be a cost-effective replacement with similar learning outcomes. McCusker, Almaghrabi, and Kucharski (2018) developed the “Virtual Electronic Laboratory” based on a real laboratory. The lab environment was constructed using the Unity3D Game Engine for room-scale VR. It provides a laboratory-based experience similar to the real laboratory while using three-dimensional virtual simulations. Electronic devices and simple electronic components that resemble the real laboratory equipment should familiarize students with the material. Furthermore, they evaluated the effectiveness of the virtual reality laboratory with 45 engineering students. The study results show that a combined approach of teaching students in both VR and the real laboratory yields the best results. Although the outcome indicates that the effectiveness of VR labs is currently not as powerful as traditional practical labs, there are areas where a virtual lab environment might be able to outperform the traditional approach. Improvements in virtual reality hardware and software open up new opportunities for future development (McCusker et al., 2018). For example, the availability of eye tracking for VR offers unique and exciting opportunities. Juvrud et al. (2018)

developed a virtual laboratory where they combined psychophysiological measures and VR. They evaluated autonomic responses, skin conductance response and pupillary dilation in response to a spider, a beetle, and a ball. The participants had higher skin conductance and pupil responses to the spider. This effect was dependent on the closeness of the stimuli to the participant. If the spider was close to the virtual self, this triggered stronger reactions. The research results show the benefit of pupil dilation as a marker for self-excitation and the ability to measure this in virtual lab environments with commercially available VR hardware.

The Steam Store[14] offers much more commercial examples of complete laboratory environments for different devices. For example, "The Lab"[15] developed by Valve is a collection of different room-scale VR experiments set in a pocket universe where make use of different aspects of VR capabilities. It demonstrates the interaction and gameplay facilities with the HTC Vive using various realistic scenarios. In eight game types, players can explore artifacts, the human body, the solar system, or how to repair a robot. Another example of the use of VR is "The VR Museum of Fine Arts"[16] where users can walk through a realistic virtual museum and look at exhibits they have never seen before. For example, the Mona Lisa, the Terracotta Arms or the Water Lilies exhibition.

2.4. Summary

Today, know-how in the disciplines of science, technology, engineering, and mathematics is increasingly in demand. Due to the lack of student's interest, it is essential to engage and enhance student's motivation and enthusiasm. Using interactive and engaging learning methods achieves an increased learning outcome. Interactive simulations, visualizations, virtual and remote labs, as well as gamified learning use the active learning approach to involve students directly in the learning process. These learning tools have proven to be an efficient way to increase the performance of students.

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[14] https://store.steampowered.com/

[15] https://store.steampowered.com/app/450390/

[16] https://store.steampowered.com/app/515020

Today's students have different needs than previous generations. They are growing up with Internet, computer games, smartphones and instant messaging. Information and Communication Technologies supports them in self-directed learning, active learning and group-based learning. The TEAL approach merges lectures, simulations, and hands-on desktop experiments to build a collaborative learning experience. Simulations and visualizations of experiments allow a better understanding of the complex processes and phenomena in a simpler and safer environment. Simulations and virtual laboratories are a cost-effective alternative for educational institutes to give students practical experience. Virtual laboratories provide a similar practical experience compared to traditional laboratories. Using gaming aspects in simulations results in a more engaging experience and increases the learning outcomes. The "Virtual TEAL World" uses these techniques in an immersive, persistent multi-user environment to imitate the TEAL environment. A more immerse and engaging feeling can be obtained by using VR technologies. The interaction with the virtual environment gives the user a higher intensity of immersion by the feeling of being there. Using virtual reality in combination with virtual laboratories results in a more immersive lab experience. The already existing VR labs demonstrate a variety of application scenarios.

The next chapter describes the requirements to design and adapt the concepts of a 3D virtual physics laboratory environment. The goal is to design and implement different experiments and to integrate them into an existing virtual laboratory. The main objectives are usability improvements and the improvement of the VR experience, especially the interaction with the experiments.

3. Design and Conceptual Model

This chapter gives an overview of the design and conceptual model of the immersive physical laboratory framework called Maroon, and the experiments integrated into Maroon. It describes the user target group, the system requirements, the structure of the lab and the experiments. We start by introducing the existing model, which provides a framework for a modular and extensible laboratory environment and further experiments which should be integrated. The implementation of the new experiments should be simple and straightforward. The goal is to combine design features based on immersion and engagement in order to create more motivational and interactive experiments. Specially designed simulations should help gain a better understanding of the underlying physical phenomena. While the traditional desktop application provides high availability, the use of immersion techniques increases motivation and engagement. The next section gives an overview of the existing system that is used as a starting point.

3.1. Starting Point and Motivation

Maroon is an award-winning[1] interactive physics laboratory and experiment environment developed to visualize and simulate various experiments. It allows creating different modules and users to load these contents into learning stations. Maroon supports various technologies such as virtual reality devices, mobile technologies, or web-based applications to take advantage of different interactive engagement and immersion strategies. Figure 3.1 shows the main laboratory scene. Experiments and learning activities are organized as learning station highlighted with a pink point

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[1] GOLC Online Laboratory Awards for the Best Visualized Experiment

in front of the station. The lab contains currently two activities, a quiz and a whiteboard with different learning lessons about the physical basics, and two experiments with a Van de Graaff generator. The first experiment demonstrates the electric field of a grounding sphere and a Van de Graaff generator. Users can move the grounding sphere and observe how the electric field changes, while visualizing the field with field lines. In addition, voltage and charge are shown. The second experiment is about a balloon and a Van de Graaff generator where the balloon is placed between the generator and a grounding sphere. It shows the behavior of the balloon when charging the generator (see Figure 3.2). Both experiments are designed to help students become familiar with electrostatic phenomena without any risk (Pirker, Lesjak, & Guetl, 2017).

The goals of this thesis are as follows:

- extend the existing laboratory environment by the following experiments:
    - Falling Coil
    - Faraday's Law
    - Capacitor
    - Huygens Principle
- improve VR experience.
- improve the graphical user interface for the desktop application.

For educational use at schools and universities, the experiments have to fulfill different scenarios and features. The next sections describe the user group and their requirements to customize the system according to their needs.

3.2. User Target Group

For schools and universities, it is difficult to motivate their students for STEM disciplines. They find these subjects uninteresting and do not understand why they have to learn them. Furthermore, today's students learn knowledge and skills in a different way than their previous generation.

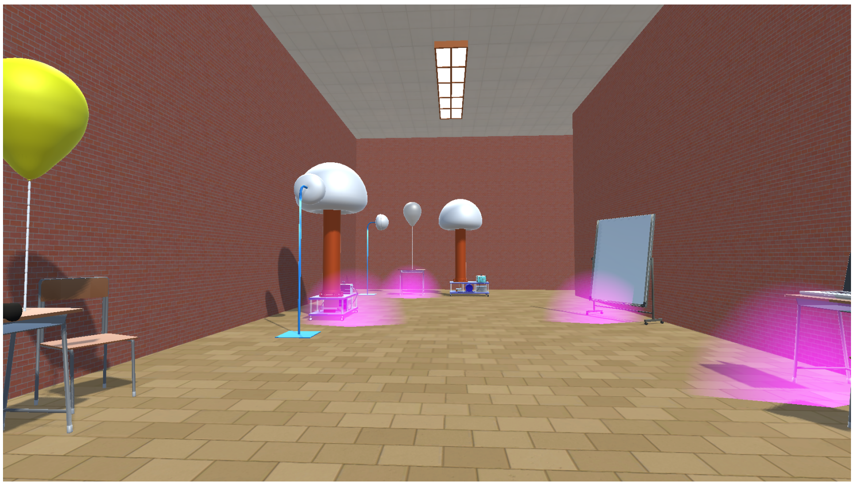
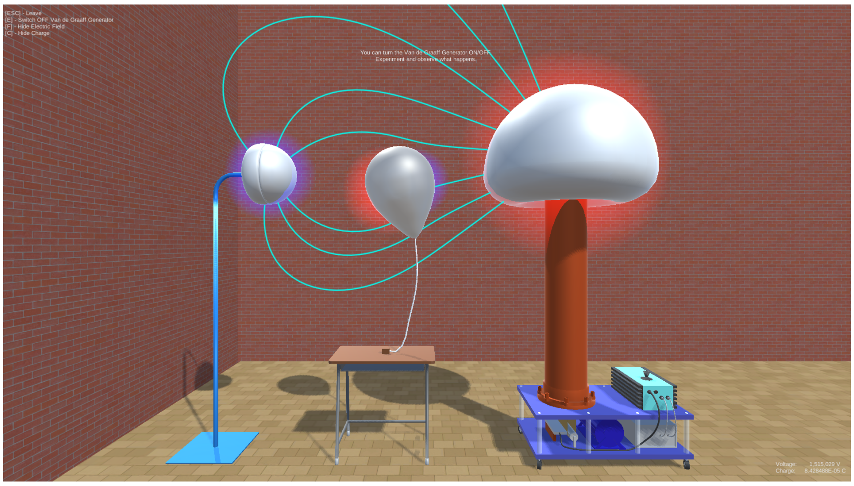


Figure 3.1.: Overview of Maroon's laboratory interface with different stations as starting point for different experiments (adapted from Pirker, Lesjak, and Guetl, 2017)



You can turn the Van de Graaff Generator ON/OFF.
Experiment and observe what happens.

Voltage: 1,515,029 V
Charge: 8.428488E-05 C

Figure 3.2.: Van de Graaff generator in Maroon (adapted from Pirker, Lesjak, and Guetl, 2017)

Their learning practices are usually more engaged, self-directed, and flexible. However, the active involvement of students in learning activities is still a major challenge (Reeve et al., 2004). Maroon is trying to address this generation of learners by providing immersive and engaging learning methods. Students are placed into a laboratory scene and take on a laboratory assistant role. While students fully immerse in the virtual learning environment, they are able to explore various experiments. This should increase the students motivation and enthusiasms in physics. The goal is to make physical phenomena understandable for everyone. Therefore, simulations and experiments must be designed in such a way that they are interesting and easy to use. The following section specifies the system requirements and describes what the system should do.

3.3. Requirement Analysis

The identification of the software requirements is a central part of the software engineering process. They describe the services provided by the system and its operational constraints. These requirements reflect the needs of users and can be classified into functional requirements and non-functional requirements. Functional requirements describe the services the system should provide, specific input reactions, and the behavior in certain situations. In contrast, non-functional requirements describe requirements that do not directly affect the specific functions to be performed by the system. These could be constraints on the services of functions offered by the system (Sommerville, 2007). Regarding the requirements of implementing experiments for an immersive virtual laboratory, the user target group, as mentioned before, has to be considered. The following sections specify the functional and non-functional requirements that the system should satisfy.

3.3.1. Functional Requirements

The goal of Maroon is to create an interactive physics laboratory and experiment environment for active learning in the classroom or at home. The laboratory framework should provide simulations and experiments that can be easily adapted and extended for the use of PC or VR solutions. The following list gives a collection of functional requirements that the experiments should meet:

1. Experiments and Simulations
    1.1. The Experiments should be represented by a lab station which should act as an entry point.
    1.2. Experiments should be set up in single rooms where users can run the experiments.
    1.3. Users should be able to
        a) select the new experiments from the main laboratory scene.
        b) change physical parameters to influence the experiment outcome.
        c) start, pause and stop the experiment.
        d) leave the experiment room.
        e) change the current language.
2. Falling Coil and Faraday's Law Experiment
    2.1. Users should be able to
        a) vary the magnetic moment.
        b) vary the ring resistance.
        c) adjust the number of field lines.
        d) adjust the resolution of the vector field.
    2.2. The induced current should be displayed on a screen.
    2.3. In Faraday's Law experiment, users should be able to move the magnet fixed on the horizontal axis.
3. Capacitor Experiment
    3.1. Users should be able to
        a) change the power voltage value.
        b) change the the dielectric material.
        c) adjust the number of field lines.
        d) adjust the resolution of the electric field.
        e) vary the distance between the plates.
        f) change the size of a specific capacitor plate.
        g) set charges into the electric field.

   3.2. The charging/discharging process should be displayed on a screen.
   3.3. The capacity of the capacitor should be visible at any time.
   3.4. The current flow should be be visualized by moving charges.
   3.5. The capacitor plates should be colored according to their charge.
4. Huygens Principle Experiment
   4.1. Users should be able to
      a) change the slit plate.
      b) move the slit plate.
      c) vary the wave frequency.
      d) vary the wave length.
      e) vary the wave amplitude.
      f) change the wave propagation mode.
      g) adjust the wave color.
   4.2. Adjustments should only be possible for meaningful values to ensure a noticeable wave propagation.
5. VR-Specific
   5.1. Users should be able to
      a) reach all interactive objects without teleporting.
      b) change parameters via a virtual control panel.
      c) feel acting forces through haptic feedback.
      d) take notes about theoretical explanations on a virtual board.
      e) choose a specific visualization color via the touchpad on the controller.
   5.2. Users should not be able to teleport within the experiment rooms to prevent unintentional movement.
   5.3. Interactable objects should be highlighted when touched.
6. PC-Specific
   6.1. Users should be able to change parameter via a graphical user interface.
   6.2. Users should not be able to move in experiment rooms.
   6.3. The experiment view should be fixed to ensure a good observation.

3.3.2. Non-Functional Requirements

In contrast to functional requirements, non-functional requirements are requirements that do not directly affect the specific function which should be performed by the system. They are software features such as usability, response time, reliability, resource usage, maintainability, availability, and compatibility. The non-functional requirements are defined as follows:

1. Usability
    - 1.1. The experiments should be intuitive to use and easy to learn.
    - 1.2. Users should be able to detect interactable objects easily and should be able to use them without explanation.
2. Response Time
    - 2.1. System interactions should be executed without any delay.
    - 2.2. Switching between laboratory scene and experiment scene should be possible with loading times less than five seconds.
    - 2.3. Physics calculations should be frame-rate independent.
    - 2.4. The VR application should have a sufficient frame rate to provide a fluid image.
    - 2.5. Extensive calculations and visualizations should not restrict the user in any way.
3. Reliability
    - 3.1. The system has to ensure that the simulations and calculations are correct and realistic.
4. Resource Usage
    - 4.1. The system should require low CPU resources and memory to provide a high frame rate.
5. Maintainability
    - 5.1. The experiments should be modular so that it can be easily expanded.
    - 5.2. Further changes should be possible without much overhead.
    - 5.3. Interfaces should be designed in such as way that they can be easily extended and reused.
6. Availability

   6.1. The system should be able to run the experiments for a longer duration without restarts.

7. Compatibility
   7.1. The experiments should be compatible with the current laboratory framework.
   7.2. The experiments should support interactions with the HTC Vive.

In Summary, Maroon should be a user-friendly, engaging, and immersive virtual physic laboratory, where students can learn physical phenomena by doing practical experiments. It should enhance the student's conceptual understanding through simulations and visualizations. The experiments should be structured so that elements can be reused and easily adapted. The next section describes the conceptual structure of the laboratory environment in which the experiments will be integrated.

3.4. Maroon the Immersive Physics Laboratory

Maroon is designed as an interactive, extensible virtual laboratory environment that allows students to learn physical phenomena in an immersive and motivating way (Pirker, Lesjak, & Guetl, 2017). In order to develop such a 3D learning environment, it requires a development platform that allows creating a three-dimensional virtual learning environment. A tool that fulfills this criterion is Unity3D[2]. It is a cross-platform game engine which allows creating three-dimensional, virtual- and and augmented reality applications, as well as simulations. Unity3D supports 2D and 3D graphics and asset import. In addition, it allows to assemble imported object into scenes and environments. Unity's built-in physics engine includes components that handle acceleration, collisions, gravity, and other forces (Unity, 2019g). Maroon extends the physics engine and builds a new physic layer on top of the engine. The experiments based on this layer and provide physical modifications and visualizations. The different variants of Maroon support several forms of virtual learning experiences. Figure 3.3 gives a conceptual overview of the different versions of Maroon. Each version supports

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[2] https://unity.com/

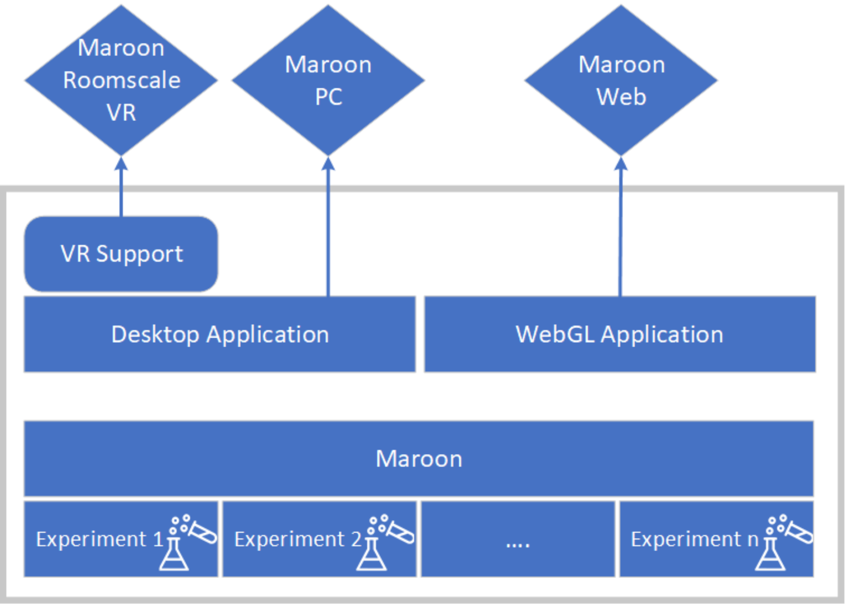

Figure 3.3.: A conceptual overview of the different variants of Maroon (Maroon Desktop, Maroon Room-Scale VR, Maroon Web)

different forms of usability, engagement, and immersion through diverse activities and interactions.

3.4.1. Conceptual Architecture

Maroon is designed as a classical physics laboratory with various stations, each representing a different experimental set-up or activity. The main laboratory room acts as a three-dimensional menu where users can choose an experiment or activity by navigating to the specific station. Each learning activity is highlighted with a colored point in front of the station and acts as an entry point. When entering a learning activity, the user leaves the laboratory room and joins a new room which represents the experiment or the activity with the specific learning content. Figure 3.4 shows the conceptual overview of the laboratory with various experiment stations including special activities.

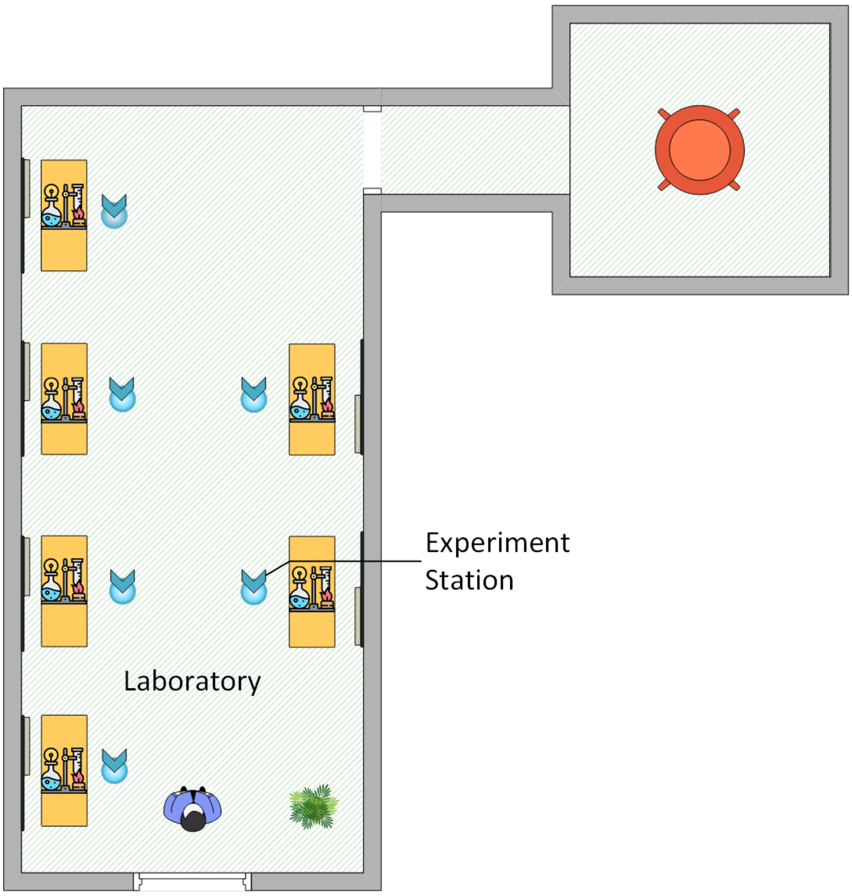

Figure 3.4.: A conceptual overview of the main laboratory room.

The laboratory is an educational environment designed for users to learn about electromagnetic and electrostatic physical concepts as well as oscillations and waves through various experiments and visualizations. In this three-dimensional experimental environment, users can perform experiments which are often difficult, too expensive or too dangerous in the real world. Figure 3.5 shows the conceptual architecture of the new implemented components. The green components extend the existing laboratory by four experiments and improve the user interaction for the different variants. The following sections introduce the two concepts of Maroon (Maroon PC and Maroon Room-Scale VR) and the new experiments with the goal to evaluate different aspects such as usability, immersion, and engagement.

3.4.2. Maroon PC (D1)

Maroon PC is the standard version of Maroon intended for the classical PC use as a desktop application or a web application. This version is designed similar to classic computer games controlled via mouse and keyboard. Users are able to walk through the laboratory from a first-person perspective. For this, Unity provides a character controller for a first-person view which allows an easy movement constrained by collisions. The character controller consists of a capsule collider adjusted to the player's size and a camera through which the player views the world (see Figure 3.6). The component provides several properties that allow easy customization (Unity, 2019a). Table 3.1 lists the properties of the character controller.

While the arrow keys are used to move, the mouse determines the direction of view and movement. To start an experiment, the user has to navigate close enough to a specific experiment station. The experiment's user interface is specially designed for mouse control. Figure 3.7 shows the conceptual overview of the graphical user interface. The experiment in the center of the application window demonstrates the physical phenomenon and can be controlled via the control panel on the right. The panel provides control element such as sliders to adjust specific parameters of the simulation to impact the experiment outcome. The experiment can be started, paused, and reset using the control buttons at the bottom. Considering the difficulty of learning invisible physical phenomena, users can use different visualizations

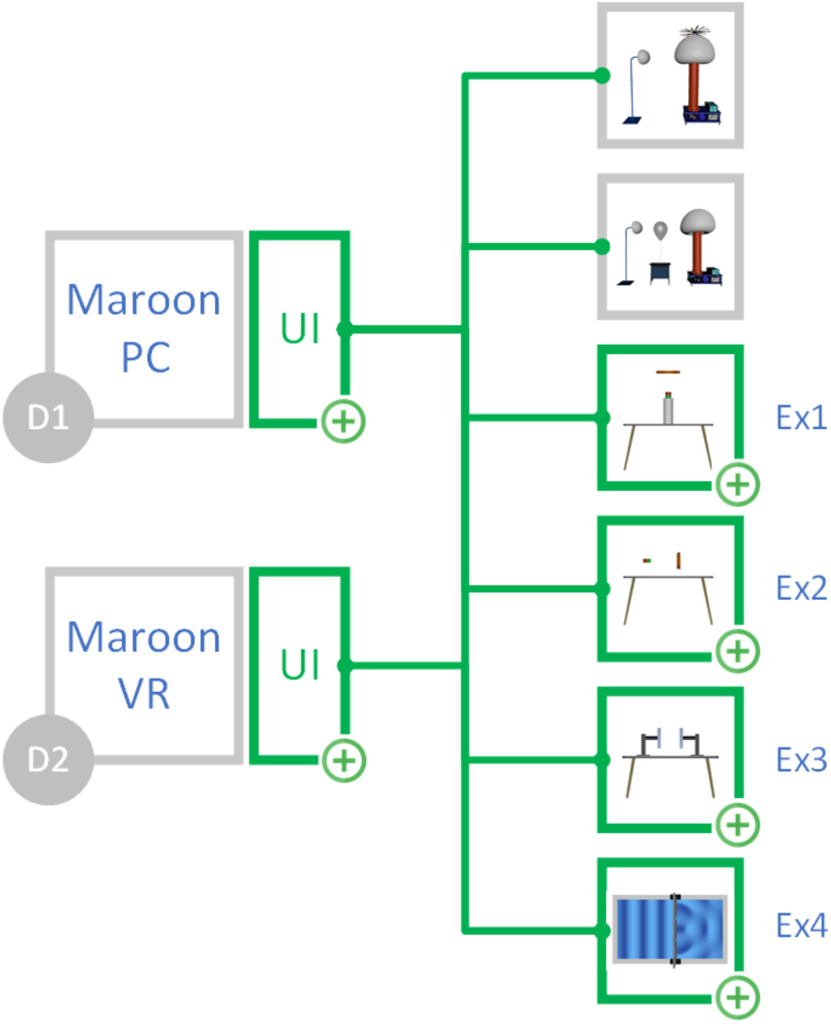

Figure 3.5.: Conceptual architecture of the new implemented components (green)

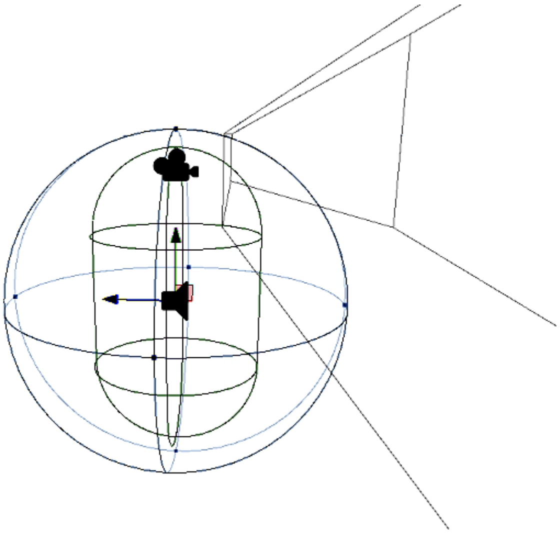

Figure 3.6.: The Character Controller used for first-person player.

Property	Function
Slope Limit	Limits the collider to only climb slopes that are less steep (in degrees) than the indicated value.
Step Offset	The character will step up a stair only if it is closer to the ground than the indicated value.
Skin width	Two colliders can penetrate each other as deep as their skin width.
Min Move Distance	If the character tries to move below the indicated value, it will not move at all. This can be used to reduce jitter.
Center	This will offset the Capsule Collider in world space, and won't affect how the Character pivots.
Radius	Length of the capsule collider's radius.
Height	The character's capsule collider height.

Table 3.1.: Character Controller Properties (Unity, 2019a)

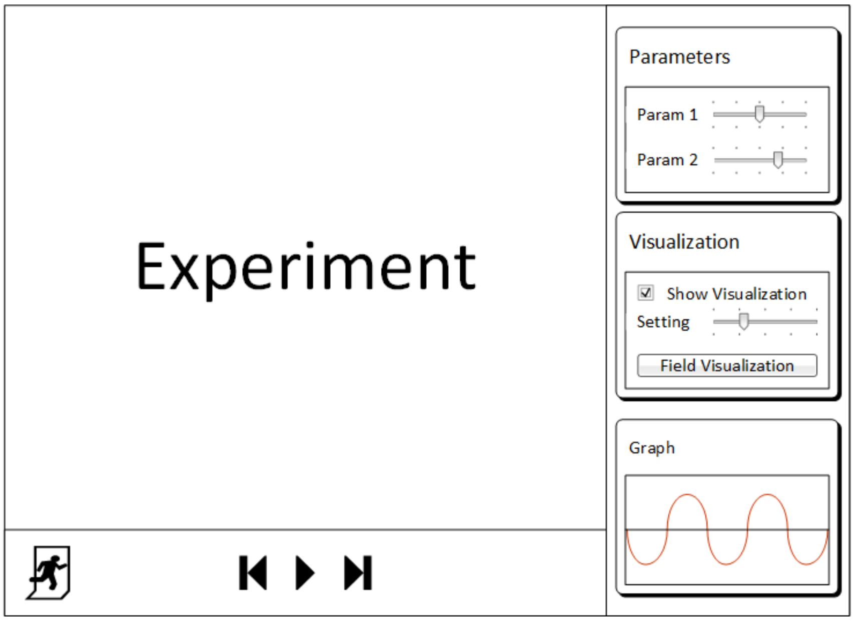

Figure 3.7.: Maroon Experiment UI concept

via the control panel to make the unseen visible and understandable. When the user is finished exploring, leaving the experiment is accomplished by pressing the exit button.

3.4.3. Maroon Room-Scale VR (D2)

Maroon Room-Scale VR is an extension of Maroon with immersion as a fundamental element. It enables a virtual reality experience based on the desktop variant and provides full immersion and concentration on the learning content. Maroon Room-Scale VR is special designed to run on the VR platforms HTC Vive and Oculus Rift. To support these two platforms, the SteamVR[3] plugin and the Virtual Reality Toolkit[4] (VRTK) were chosen. The SteamVR plugin is an extension for Unity and provides an API for all popular VR headsets. It manages the VR controllers and handles user input.

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[3] https://steamcommunity.com/steamvr

[4] https://vrtoolkit.readme.io/

It allows building a VR application from scratch by providing concrete examples of interacting with virtual objects and the API. The VRTK is a toolkit for rapidly building VR solutions in Unity and supports SteamVR and Oculus SDK. It is a set of useful, reusable scribts and components for general virtual reality problems when building a VR application. VRTK includes a number of common solutions such as (VRTK, 2019d):

- Locomotion within virtual space.
- Interactions like touching, grabbing and using objects
- Interacting with Unity UI elements through pointers or touch.
- Body physics within virtual space.
- 2D and 3D controls like buttons. levers, doors, drawers, etc.

Maroon Room-Scale VR is specially designed for the HTC Vive. The HTC Vive is a virtual reality headset including a gyro sensor, an accelerometer, and a laser position sensor for a 360-degree experience. Two base stations determine the position of the user in a room with a maximum size of 5x5 meters. Motions are tracked and transformed into the virtual space. Specially designed controllers allow interaction with virtual objects and the environment. The controllers combine 24 sensors, a multi-function trackpad, a two-stage trigger, and a haptic feedback function (HTC, 2019). One of the biggest challenges of virtual reality is locomotion. In room-scale VR, users can walk freely in the room but are limited in their movement. Due to the space constraints, users have to become familiar with a different form of movement in order to travel greater distances in virtual reality. Teleportation is a fun and enjoyable way to overcome these limitations. It allows fast and free navigation with the advantage that users do not get sick. Although this form of movement is not natural, users are accustomed to the concept of teleportation from science fiction. For teleporting to a specific position, the user has to press the touchpad on the controller. A colored laser beam acts as a pointer and allows the user to aim at the target location. Experiments and activities can be started by using the information panel in front of the station which acts as a portal into the experiment room. Each experiment is designed especially for VR so that users can interact with all interactable objects without teleporting. In order to facilitate the detection of interactable objects, they are highlighted when touched. Users can adjust specific parameters and change the visualizations by using a virtual control panel. The control panel contains sliders which can be moved by the controller and a display which shows the current value according to the position of the slider. After exploring the experiment, the user can leave the experiment room by using the door handle. The next section describes the conceptual design of the simulations and experiments.

3.5. Simulations and Experiments

This section will introduce the conceptual design of the experiments and simulations implemented in Maroon. The goal is to simulate and illustrate different physical phenomena by providing various virtual experiments. Maroon is extended by experiments in the field of electromagnetic and wave propagation. Each experiment scene implements the general experiment and extends it with the respective user interface, as seen in Figure 3.8. The experiment is fully functional on its own and contains all physical relevant components, including visualization elements. The following subsections describe the different experiments that have been realized in this thesis. The *Falling Coil* and *Faraday's Law* experiment is based on Holly, Schiller, and Schinnerl (2016).

3.5.1. Falling Coil (Ex1)

The Falling Coil experiment demonstrates the dynamics between a permanent magnet and a conductive non-magnetic ring (see Figure 3.9a). The magnet is positioned above a table and interacts with the coil falling down because of gravity. When the coil enters the magnetic field of the magnet, it induces an electric current. This leads to a magnetic field created by the coil, which interacts with the magnetic field of the magnet. If the current is high enough, the acting force pushed the coil upwards. However, the experiment output depends on the parameters of the coil and the magnet. The coil is defined by its mass, resistance, and self-inductance. The magnet is characterized by its magnet dipole moment. Users can change these parameters to observe the change in magnetic flux and the induced current. Additional visualizations such as field lines, vector fields or iron filling

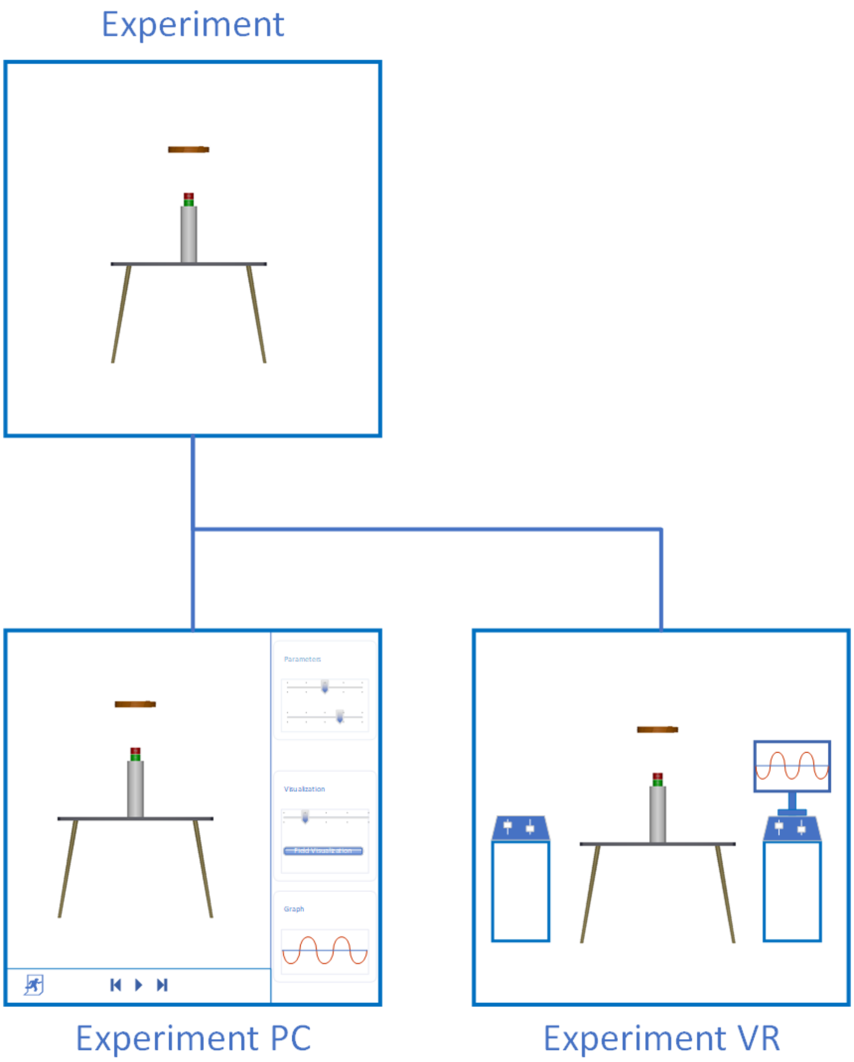

Figure 3.8.: Different user interfaces based on the general experiment

make the experiment more interactive and allow the user to see invisible phenomena to get a better understanding of the underlying concepts.

3.5.2. Faraday's Law (Ex2)

The Faraday's Law experiment is designed similarly to the Falling Coil experiment and shows the induction principle of a coil in a magnetic field. The magnet and the coil are both constrained on the horizontal axis (see Figure 3.9b). In this experiment, the user is able to move the magnet, which changes the magnetic flux through the coil. This leads to an electric current and produces another magnetic field which interacts with the permanent magnet. The interaction options are very similar to the falling coil experiment. The user is able to change the ring resistance, the magnetic dipole moment, and the visualization of the magnetic field. The special feature of this experiment is that the VR version allows the user to feel the acting force through haptic feedback. The controller vibration intensity is equal to the force and gives the user an even more immersive experience.

3.5.3. Capacitor (Ex3)

The Capacitor experiment demonstrates the storage of energy in an electric field. Figure 3.9c shows the conceptual overview of the experiment setup. The main components of this experiment are two electrically conductive surfaces which are separated from each other by an insulating material. The capacity of the capacitor depends on the plate distance, the overlapping area and the dielectric material. By changing these parameters, the user can observe how those parameters affect the resulting capacity. Furthermore, the user can change the voltage of the power source and the visualization of the electric field such as the number of field lines and the resolution of the vector field. When the simulation is started, the capacitor is charged or discharged to the adjusted voltage. The charging and discharging process is shown via a graph and by charges which move from one plate to the other plate. The intensity of the plate colour indicates the charge value. A negatively charged plate is shown as blue and a positively charged plate as red. Additionally, the user has the possibility to place charges into the electric field in order to observe the deviation.

3.5.4. Huygens Principle (Ex4)

Since all previous experiments show an electromagnetism concept, the Huygens principle is the first approach to create an experiment which demonstrates a different physical phenomenon. The experiment shows the physical model of diffraction by using water waves. For this, the experiment room contains a basin filled with water where the user can observe the wave propagation. An illustration of the basin is shown in Figure 3.9d. To demonstrate diffraction, a replaceable slit plate is placed into the basin. The user can replace them by another plate with a different number of slits. Behind the plate a interference pattern occurs created by diffraction. In order to influence the experiment, the user is able to change the wave amplitude, the wave length, the wave frequency and the propagation mode. These changes have a direct effect on the interference pattern behind the plate. In order to get a better differentiation between peak and trough, the user has the possibility to change the wave color freely.

3.6. Summary

This chapter described the design and the conceptual model of Maroon and the new implemented experiments included into the laboratory. Maroon, as an interactive and extendable physics laboratory environment, acts as a starting point for this thesis. It supports different technologies with different levels of immersion and engagement. Maroon is designed to teach students physical concepts in a motivating and effective way. The main target group of the system are students with little interest in STEM disciplines. Their needs were an essential part during the requirements definition process. The resulting system requirements describe what the system has to fulfill. Maroon should provide a user-friendly, engaging, and immersive virtual laboratory environment, where students can explore physical phenomena

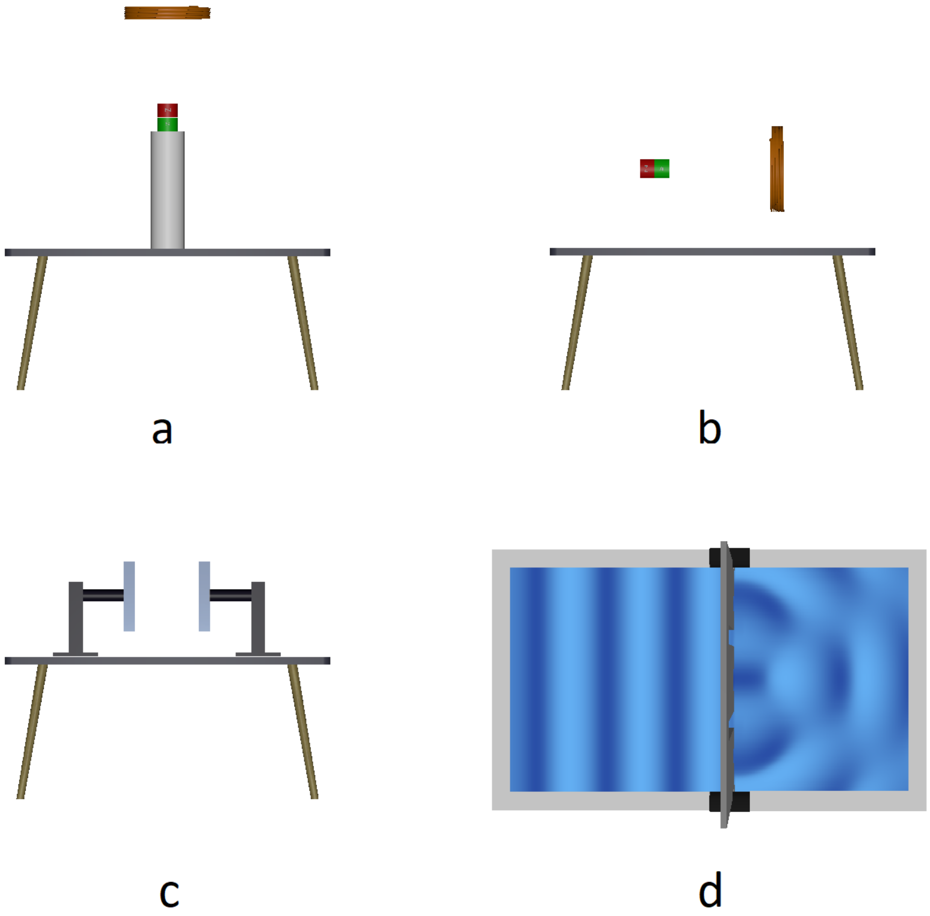

Figure 3.9.: Conceptual overview of the falling coil (a), the Faraday's law (b), capacitor (c), and the Huygens principle experiment (d)

in different experiments. Each experiment is represented by an experiment station in the main lab and acts as an entry point. The lab provides the basic functionality for the different versions of Maroon. MaroonPC is the standard version where the user interacts with the environment via mouse and keyboard. A specially designed graphical user interface provides different control elements to change parameters and to influence the experiment outcome. Maroon Room-Scale VR extends the standard version and enables a room-scale virtual reality experience. It is custom-built to run on the HTC Vive using the SteamVR plugin and the Virtual Reality Toolkit (VRTK). Each experiment is specially designed and adapted for the specific version of Maroon and comes with an individually customized user interface. While the Falling Coil, Faraday's Law, and the Capacitor experiment show electromagnetic phenomena, the wave propagation experiment demonstrates the physical model of diffraction. In order to implement these experiments, the next chapter focus on the physical fundamentals.

4. Physical Fundamentals

Physics explores fundamental phenomena and laws in our world. It enables the explanation and prediction of many natural aspects. Nowadays, computer simulations have become an essential methodology in physics. They combine theory and experiment to obtain predictions from theory. The basis of every simulation is a model that describes reality within the scope of certain approximations. Formulas and equations describe the mathematical and physical correlations of the modeled system (Feynman, 1982). In order to realize simulations in software, it is necessary to understand the physical fundamentals. This chapter describes the physical concepts of the electric and magnetic field and the Huygens principle, which are essential for the simulations and experiments in this thesis.

4.1. Electric Field

An electric field is a physical state that exists in the surroundings of an electrically charged element. It exerts mechanical forces on other charges in the field. Due to the structure of matter, quantities of electricity are present in every physical body. The smallest elementary charge is $e = 1.602191 \cdot 10^{-19}$ and is specified in Coulomb (C). It occurs in two complementary forms, as a proton or as an electron. In electrically neutral elements, equal amounts of positive and negative charges are present. If the number of positive and negative charges varies, the element is called electrically charged. For example, rubbing plastic with a woolen towel results in an unbalanced number of charges. Thereby, electrons are removed or added to the surface. Another way of separating charges and thus establishing an electric field is to apply a voltage to two metal plates which are isolated from each other. Due to the applied voltage, the charges are moved. This results in a lack of

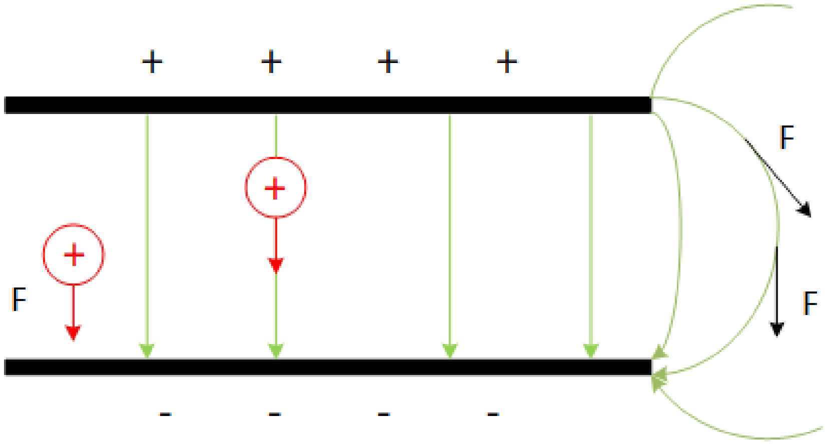

Figure 4.1.: Force effect on a charge, field lines.

electrons on one plate and an excess of electrons on the other plate. When switching off, the charges of the plates is retained because the electrons cannot move back. Such a plate construction is called a capacitor and will be discussed in Section 4.2. If a charge is set into such an electric field, it moves in the direction of the force acting on it. The path on which this movement takes place is called the field line. The field lines leave the positive electrode and enter the negative electrode, as shown in Figure 4.1. The electric field can be described by the vector field of the electric field strength $\vec{E}$. It is defined as (Chakravorti, 2017; Deimel, Hasenzagl, Krikava, Ruhswurm, & Seiser, 2005)

$$\vec{E}(\vec{p}) = \frac{\vec{F}(\vec{p})}{q}. \tag{4.1}$$

4.1.1. Coulomb's Law

Coulomb's law is the basis of electrostatics and was found by Charles A. Coulomb in 1785. The following explanation is based on Pramanik (2008). Coulomb's law describes the force between two point charges. The force is proportional to the product of the charges and to the square of the distance between them. Depending on the sign of the charges, the force acts along the line attracting or repulsive. Hence the force between two charges q_1 and q_2 separated by a distance r, is given by

$$F = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r^2} \tag{4.2}$$

where ϵ_0 is the permittivity of free space and has the value $\epsilon_0 = 8.854 \cdot 10^{-12}\frac{C^2}{Nm^2}$.

The general vector notation is defined as

$$\vec{F}_{12} = \frac{q_1 q_2}{4\pi\epsilon_0 r^2} u_{12}. \tag{4.3}$$

where $\vec{F}_{12}$ is the force acting on q_2 caused by q_1, and u_{12} is the unit vector directed from q_1 to q_2. In case of more than two charges, the individual force vectors are added according to the superposition principle. If there are the charges $q_1, \ldots, q_n$ at the positions $\vec{p_1}, \ldots, \vec{p_n}$, then the force on the charge q at the point $\vec{p}$ is given by

$$\vec{F}(\vec{p}) = \sum_{k=1}^{n} u_{kp} \frac{q q_k}{4\pi\epsilon_0 r_k^2} \tag{4.4}$$

where r_k is the distance between q_k and q, and u_{kp} is the unit vector in the direction of p_k. According to Coulomb's law, the field strength at a given point is then given by

$$\vec{E}(\vec{p}) = \sum_{k=1}^{n} u_{kp} \frac{q_k}{4\pi\epsilon_0 r_k^2}. \tag{4.5}$$

4.1.2. Motion of Charges in an Electric Field

An important application of electric and magnetic fields is the motion of charges. As mentioned before, if a charge is placed into an electric field, a force acts on it and moves it in the direction of the force. The path of the particle depends on the direction of the initial velocity. A movement in direction or against the field direction results in motion with uniform acceleration. For example, this acceleration can be used to generate an electron beam. The deflection by the electric field is used in a cathode-ray tube to produce images on a screen. The following explanation is based on Salazar Bloise, Medina Ferro, Bayón Rojo, and Gascón Latasa (2017). According to Newton's law, force is defined as

$$\vec{F} = m\vec{a} = q\vec{E} \tag{4.6}$$

where $\vec{a}$ is the acceleration and m the mass of the charge. Consider a charge q moves with horizontal velocity v_x, enters an electric field with strength E as shown in Figure 4.2. If the charge moves into the field region, it deviates towards the positive plate. According to the superposition principle, the trajectory of the charge is the result of a constant movement v_x in the x-direction and a uniform acceleration $a = \frac{qE}{m}$ in the y-direction. Therefore, the velocity in y-direction is $v_y = \frac{qE}{m}t$ with $t = \frac{x}{v_x}$. The overall velocity of the charge when leaving the electric field is then

$$v = \sqrt{{v_x}^2 + {v_y}^2} \tag{4.7}$$

with a deviation of

$$y = \frac{1}{2}\frac{qE}{m}\frac{x^2}{{v_x}^2} \tag{4.8}$$

In summary, The deviation of a charge, which is shot vertically to the field lines, is proportional to the field length and to the electrical field strength. A capacitor is an electrical component that can be used to generate an electric

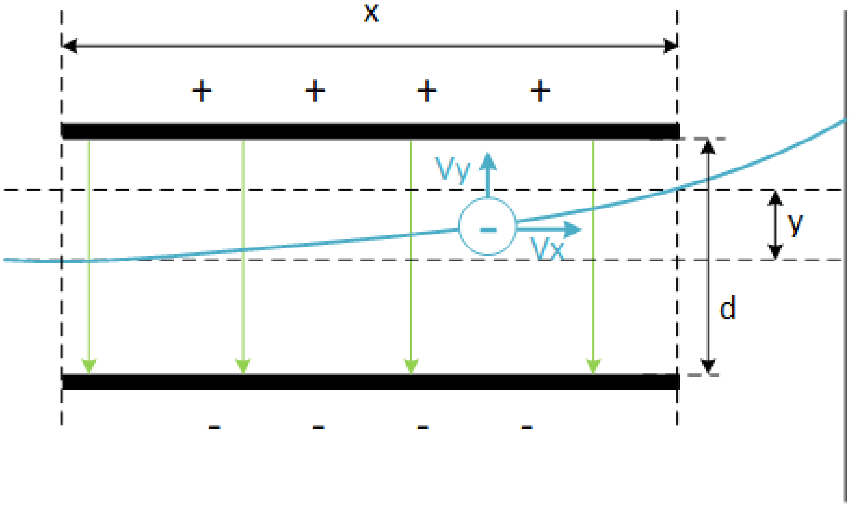

Figure 4.2.: Motion of an electron with constant velocity in an electric field

field. Thus, the deviation decreases with an increasing plate distance or voltage. The next sections describe the electrical concept of a capacitor.

4.2. Capacitor

A capacitor is a passive component that stores electrical energy in an electric field. It consists of two metal electrodes insulated from each other. The stored energy is proportional to the potential difference between the two electrodes. The proportionality factor is called capacity. Capacitors have a wide range of applications. They are frequency-determining elements in oscillation circuits and block DC voltages in high-frequency circuits. Furthermore, capacitors are elements for smoothing power supply voltages, reactive power compensation, and starting and running motors. Usually, the shape and dimensions of the electrodes are known. The field strength E and the voltage U occurring between the two electrodes results from the electric flux density obtained from the total charge Q and the area A. As the voltage is proportional to the charge, the capacity of the capacitor depends solely on its structure. The simplest form of a capacitor is the plate capacitor (see

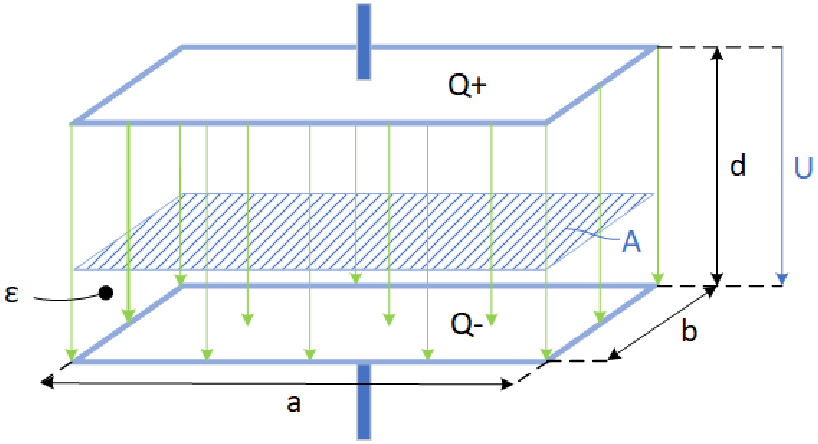

Figure 4.3.: Structure of a plate capacitor

Figure 4.3). It consists of two metallic plates, placed as close as possible to each other. Using a nonconductor (dielectric) between the two plates allows a small plate distance, which increases the capacity of the capacitor. The capacity is given by (Deshpande, 2012)

$$C = \frac{Q}{U} = \frac{A\epsilon}{d} \tag{4.9}$$

The following sections describe the behavior of a capacitor in a direct current (DC) circuit when charging and discharging.

4.2.1. Charging

After applying a DC voltage to a capacitor with a resistor in series, an electric current flow. The voltage source attracts the electrons from one plate and presses them onto the other plate. During this process, the capacitor is charged. The longer the charging process takes, the less current flows. As the current drops towards zero, the voltage rises from zero to maximum, as seen in Figure 4.4. The higher the voltage, the higher the resistance of the capacitor. Once the capacitor voltage has reached the charging voltage, no current flows and the capacitor acts as a barrier for the direct current.

Figure 4.5a shows an electric circuit with a capacitor C, a resistor R and a voltage source U_0. By turning S on, the capacitor C will be charged to the voltage U_0. In such a closed circuit (mesh), there are partial voltages. According to Kirchhoff's law, the directed sum of all voltages is zero. This gives us the equation

$$U_R(t) + U_C(t) - U_0 = 0. \tag{4.10}$$

Substituting the voltages results in the differential equation

$$\begin{aligned} RC\frac{dU_C(t)}{dt} + U_C(t) &= U_0 \\ \frac{dU_C(t)}{dt} + \frac{1}{RC}U_C(t) &= \frac{1}{RC}U_0. \end{aligned} \tag{4.11}$$

Solving this equation gives us the capacitor voltage (in time) during the charging process.

$$U_C(t) = U_0 \cdot (1 - e^{-\frac{t}{RC}}) \tag{4.12}$$

This implies, if capacity and resistance decrease, the charging becomes faster. Therefore, the time factor can be defined as $\tau = RC$. With a charging time of τ, a capacitor reaches a voltage of $0.632U_0$. After 5τ, the capacitor is 99% charged.

4.2.2. Discharging

The capacitor acts similar to a voltage source with low internal resistance. If the capacitor is disconnected from the voltage source, energy and charges are retained and the voltage remains. By connecting a load, the electric field strength and the capacitor voltage decreases. The voltage decreases from the maximum value to zero. The current changes its direction and flows in the opposite direction to the charging current. At the point where no current flows, the capacitor is discharged, as seen in Figure 4.6. Figure 4.5b

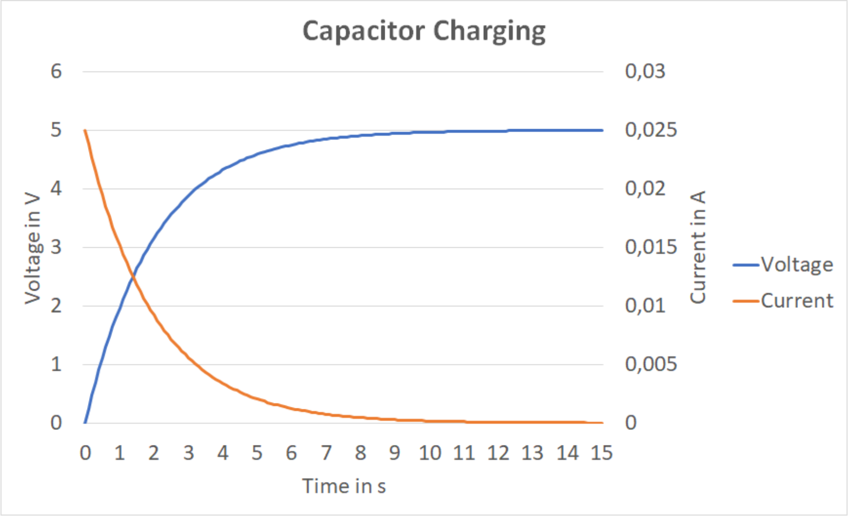

Figure 4.4.: Capacitor Charging

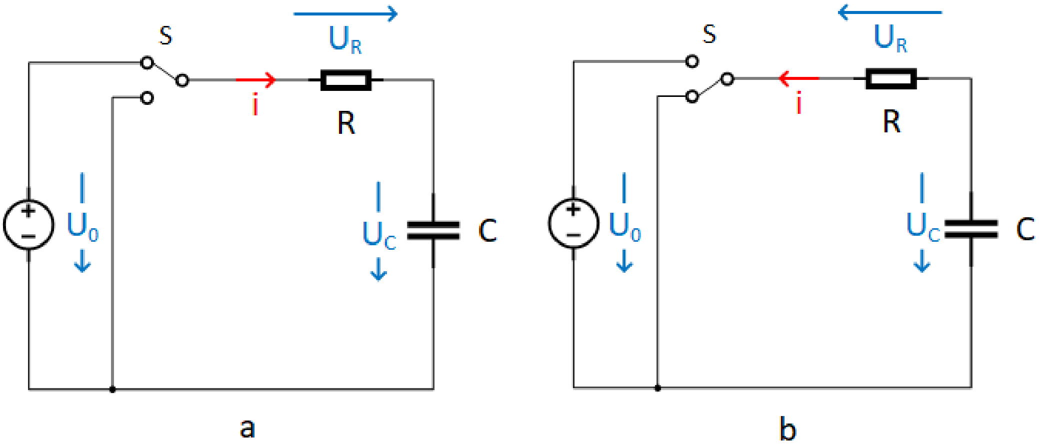

Figure 4.5.: a) RC Circuit Charging b) RC Circuit Discharging

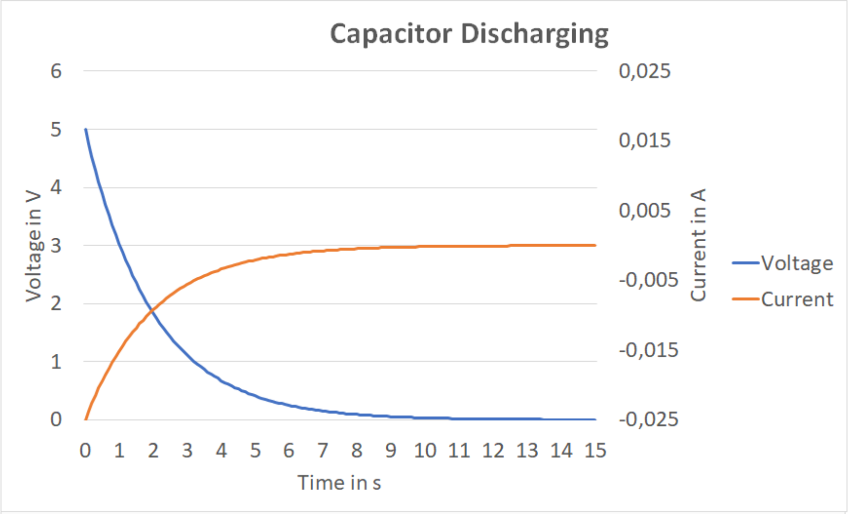

Figure 4.6.: Capacitor Discharging

shows an electric circuit in which a capacitor C discharged via a resistor R by turning S off. From this circuit and Kirchhoff's law, the following differential equation follows.

$$\begin{aligned} -U_R(t) + U_C(t) &= 0 \\ -\frac{dU_C(t)}{dt} + \frac{1}{RC}U_C(t) &= 0 \end{aligned} \tag{4.13}$$

Solving the equation gives us the capacitor voltage (over time) during the discharging process.

$$U_C(t) = U_0 \cdot e^{-\frac{t}{RC}} \tag{4.14}$$

Similar to the charging process, the capacitor discharges within 5τ (Robbins & Miller, 2012). Besides electric fields, the magnetic field has an essential part in physics too. The following section describes this phenomenon. It explains the magnetic field strength, the induction principle and the force effects acting in the magnetic field.

4.3. Magnetic Field

Magnetism is a physical phenomenon that acts as a force between magnets, magnetized or magnetizable objects and electrical charges, such as in current-carrying conductors. In the neighborhood of such objects, a special force field exists that attracts or repels other physical bodies. Similar to electric charges, magnetism exists in two fundamental forms called magnetic north and south poles. A magnet always consists of a north and south pole and cannot be separated. Poles of the same type repel each other, different pole types attract each other. It was a significant finding in the field of electrical engineering when the Danish physicist Christian Oersted found out that a compass needle deflected in the presence of a current-carrying wire (Ørsted, Jelved, Jackson, & Wilson, 2014). Moving electric charges generate a magnetic field in their surrounding a magnetic field. Furthermore, in a magnetic field, forces are acting on moving charges and thus also on current-carrying conductors. Therefore, a quantity of a moved electricity Q creates a magnetic field. A closed circulation of an electric current system generates a magnetic dipole with a dipole moment $\vec{m}$. Both natural and electric magnetic dipoles produce the same field profile. The magnetic flux density B of such dipoles in a point P is given by

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi}\left[\frac{3\hat{r}(\vec{m}\cdot\hat{r}) - \vec{m}}{r^3}\right] \tag{4.15}$$

where $\hat{r} = \frac{\vec{r}}{|\vec{r}|}$ is the unit vector in the direction of $\vec{r}$ and $r = |\vec{r}|$ is the distance from the magnet to the point P. The magnetic constant μ_0 specifies the ratio of the magnetic flux density to the magnetic field strength in a vacuum (Chow, 2006).

4.3.1. Magnetic Field Strength

The magnetic field strength H is a factor that determines the direction and strength of each point in space. The direction corresponds to the tangent on the field line, and the magnitude represents the strength of the magnetic field at the given point. Figure 4.7 shows the magnetic field strength of a current-carrying wire at the given point P. The field strength is given by

$$H = \frac{I}{l} = \frac{I}{2\pi r} \tag{4.16}$$

where I is the current through the conductor and l the length of the field line passing through the point. If an electrical conductor is winded, it is called an electromagnetic coil. The individual magnetic fields of each of the winding loops overlap and generate an overall field which is equivalent to a bar magnet field. The field strength inside a cylindrical coil is given by

$$H = \frac{IN}{2\pi r} \tag{4.17}$$

where I is the current through the coil, N is the Number of turns, and r is the radius of the coil. The next sections focus on the behavior of an electrical conductor in a magnetic field. The relationship between the magnetic field strength H and the magnetic flux density B is given by

$$B = \mu \cdot H \tag{4.18}$$

where μ is the permeability and describes the material characteristics.

4.3.2. Electromagnetic Induction

The electromagnetic induction is a process where an electrical voltage produced by moving an electrical conductor in a magnetic field or by changing the magnetic field. If a conductor is moved in a magnetic field, the acting force leads to a charge displacement and produce a voltage between the two ends of the conductor. Motion induction is the fundamental principle of transforming mechanical energy into electrical energy. In 1831, Faraday observed that a current flows in a closed circuit when a magnet in its vicinity is moved. The changing magnetic flux Φ is the underlying principle of this

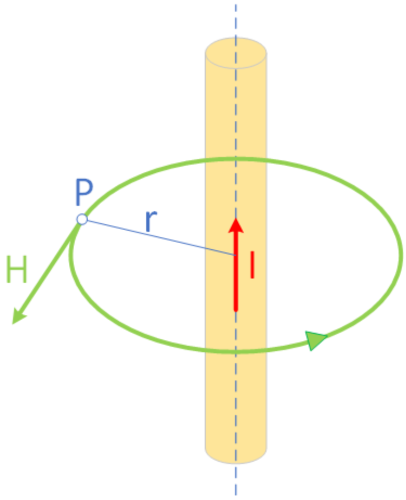

Figure 4.7.: Magnetic field strength of a current-carrying wire

effect. The magnetic flux is defined as the number of all magnetic field lines passing through an area. It is given by

$$\Phi = \int_A \vec{B}\, d\vec{A} \tag{4.19}$$

where A is the corresponding area and B is the magnetic flux density. Additionally, the induced voltage U is the negative time variation of the magnetic flux through the area of a conductor loop.

$$U = -\frac{d}{dt}\int_A \vec{B}\, d\vec{A} = -\frac{d\Phi}{dt} \tag{4.20}$$

The electrical voltage induced by a coil with N turns is then given by

$$U = -N\frac{d\Phi}{dt} \tag{4.21}$$

The current resulting from the induced voltage has the effect that forces act on the current-carrying conductor in the magnetic field. The following section describes these acting forces in detail.

4.3.3. Magnetic Force on a Current-Carrying Circuit

Consider a current-carrying conductor in a magnetic field. Due to the overlay of the magnetic fields, the field increases at one side and decreases on the other side. That deflects the conductor in the direction of the weaker field. A wire of directional length $\vec{l}$ with a constant current I transports the charge $q = It$ during the time t. Therefore, the electrons pass the wire with the velocity $\vec{v} = \frac{\vec{l}}{t}$. The force effect derives from the Lorentz force acting on each of the moving charges is:

$$\vec{F} = q\vec{v} \times \vec{B} = I(\vec{l} \times \vec{B}) \tag{4.22}$$

The corresponding magnitude is given by

$$F = I\, l\, B\, sin(\alpha) \tag{4.23}$$

where α is the angle between the wire and the magnetic flux density. If the wire is orthogonal to the magnetic field, $sin(\alpha) = 1$ and the formula can be simplified to

$$F = I\, l\, B \tag{4.24}$$

In the general form, i.e., if the wire is curved, the acting force can be determined by applying Equation 4.22 to each infinitesimal segment and adding up all these forces by integration (Deimel et al., 2005; Pramanik, 2008).

$$\vec{F} = I \int d\vec{l} \times \vec{B} \tag{4.25}$$

However, the electromagnetism phenomena are invisible to the human senses. Using field lines makes the unseen effects visible.

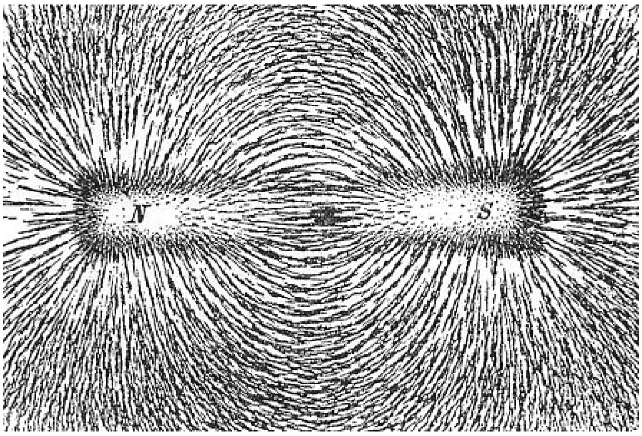

Figure 4.8.: Field lines of a bar magnet shown by iron filings on a sheet of paper (Wikimedia, 2019)

4.3.4. Graphical Representation of the Magnetic Field

Similar to the electric field, the magnetic field is shown in the form of field lines. They allow us to examine the impact and the amount of force in the magnetic field. Field lines are directed lines through points that indicate the direction of the field vector at this position. There is a field line through each point in the field where the field vector is not zero. Due to the infinite number of field lines, only a limited number is displayed in diagrams (Durrant, 1996). According to Maxwell's equations, all field lines along the magnetic field are closed because there are no single magnetic poles (Maxwell, 2010). However, this is not always the case. It is true for many idealized and symmetrical cases, but not for the general case (Morrison, 2000). Using iron filings obtains an illustrative picture of the magnetic field. The iron particles arrange themselves under the influence of force along the field lines and make the magnetic field appear, as shown in Figure 4.8.

In physics, waves of the electromagnetic field propagating through space, carrying electromagnetic radiant energy. They are synchronized oscillations of electric and magnetic fields (Pramanik, 2008). The next section focuses on wave propagation and the diffraction created by obstacles.

4.4. Huygens Principle

The Huygens principle states that every point on a wavefront acts as the starting point of a new wave. The new wavefront results from the superposition of all elementary waves. This concept was introduced by Christian Huygens to describe the propagation of light. He explained the linear and spherical wave propagation as well as the reflection and refraction (Huygens, 2012). Augustin Fresnel extended this principle in order to explain the diffraction of light. He showed that the resulting wave results from the interference of all elementary waves (Crew, 1900). Afterward, Gustav Kirchhoff demonstrated the Huygens principle by using the Maxwell equations (Klein & Furtak, 1986). The following sections describe the wave propagation, and the diffraction and interference using the Huygens principle.

4.4.1. Wave Propagation

A wave is a propagating oscillation or disturbance. Each wave propagates with a material-dependent velocity and transports energy from one point to another. The propagation within a medium takes place through the stimulation of particles to move due to already oscillating particles. All points of a medium, which are reached by a wave at the same time are on a wavefront. Therefore, all points of a wavefront have the same oscillation state. Wavefronts represent wave crests (maximum value) or wave troughs (minimum value). The distance between two wavefronts is called wavelength. Typical examples of waves are sound, water and electromagnetic waves.

Mathematically, a wave is a function $W(x,t)$ where x is the position and t is the time. Each of them can be formed by adding up sine waves. Such sine waves are characterized by their amplitude, phase, wavelength, and frequency. Where the amplitude is the maximum extent of the oscillation, the frequency is the number of wave crests that pass a point in one second, and the wavelength is the length of the shortest repeating part. The phase specifies how much the oscillation is shifted in time. The propagation speed is given by

$$c = \lambda f \tag{4.26}$$

where λ is the wavelength and f is the wave frequency (Elmore & Heald, 2012; Graff, 2012). If the coordinate system set so that one axis corresponds to the propagation direction, the deflection of the wave can be described as follows

$$W(x,t) = A \cdot cos\left(2\pi f\left(\frac{x}{c} - t\right) + \varphi\right) \tag{4.27}$$

where A is the amplitude, f the wave frequency, c the propagation speed, and φ the phase (Brekhovskikh, 2012). If there are multiple wave sources, the waves overlap according to the superposition principle. The next section describes the interference of waves and the principle of diffraction.

4.4.2. Diffraction and Interference

As mentioned before, a wave is a disturbance in the medium which causes the particles of the medium to oscillate. Whenever a wave hits an obstacle, diffraction occurs. Diffraction is the result of the formation of new waves along a wavefront according to the Huygens principle. Every point of a wavefront acts as an elementary wave. The superposition of all these elementary waves result in the new wavefront, which is usually identical to the old one. If there is an obstacle, the elementary waves cannot interfere with partial waves at the edges of the obstacle. Therefore, they propagate as spherical waves and enter the area behind the obstacle. The intensity of this diffraction wave resulting from the interference of the elementary waves involved is strongly direction-dependent so that a diffraction pattern generates. Therefore, diffraction only takes place together with interference.

Interference describes the change of the amplitude when two or more waves overlap. There are two different types. Destructive interference, where the waves erase each other and constructive interference, where the amplitudes increase. If several waves overlap at the same position, the resulting wave field is calculated by (Cowley, 1995)

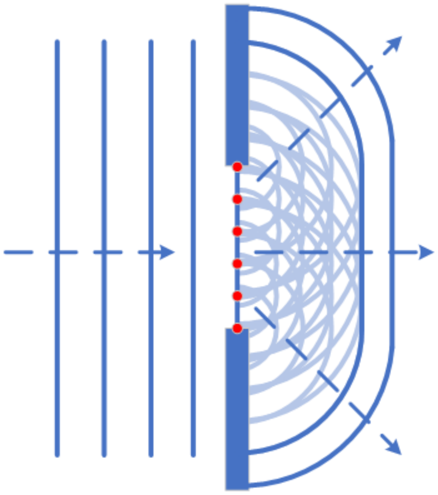

Figure 4.9.: Wave diffraction according to Huygens principle

$$W(x,t) = \sum_i W_i(x,t) \tag{4.28}$$

A well-known example of diffraction is the double slit experiment. In 1802, Thomas Young showed in this experiment the wave nature of light. In the experiment, waves pass through two small parallel slits and show an interference pattern. This pattern is created by diffraction of the wave propagation at the double slit (Born & Wolf, 2013). For the sake of simplicity, Figure 4.9 shows the diffraction at a single slit. The resulting wavefront behind the plate is the superposition of the elementary waves starting from the red points on the wavefront at the slit.

4.5. Summary

This chapter discussed the theoretical fundamentals which are necessary to implement the experiments mentioned in section 3.5. The equations and formulas in this chapter model the physically-correct real world. After explaining how electrical energy can be stored in an electric field, and which forces acts on charges in an electric field, the magnetic field and the principle of electromagnetic induction was carried out. The chapter concludes by demonstrating wave diffraction according to the Huygens principle. It is worth pointing out, that due to the complexity of the necessary physics calculation, several optimization steps have to be considered in order to provide a fluent real-time simulation. The implementation of the experiments will be the topic of the next chapter.

5. Development Details

This chapter describes the development of the physics simulations based on the requirement list and the conceptual model defined in chapter 3. After a short introduction of the experiment architecture and the specific control elements, the development details of the physical components are discussed. Finally, the different visualizations of the physical phenomena are described.

5.1. Architecture

As mentioned in Section 3.4, Maroon is an extendable physics laboratory framework and builds a layer on top of the Unity physics engine which provides the basic functionality for experiments. Each experiment is designed to run in a single experiment room and contains all physical relevant components, including visualization elements. The experiment is saved as prefab, which allows the storage of objects with all its components and properties. The prefab acts as a template for platform-specific implementations and allows for changes to all its instances. Figure 5.1 shows the conceptual experiment architecture and the involved components. The `SimulationController` handles the simulation process and provides methods to start or stop the simulation. It contains a list of resettable objects to reset the whole simulation to its initial state. Furthermore, it allows setting a simulation time scale at which the time is passing. The visualization components provide different modules and methods to illustrate the underlying physical phenomena. The details of the different visualization techniques are described in section 5.5. Depending on the platform, users interact with the system using a graphical user interface or virtual control elements. The next section introduces the different user interfaces.

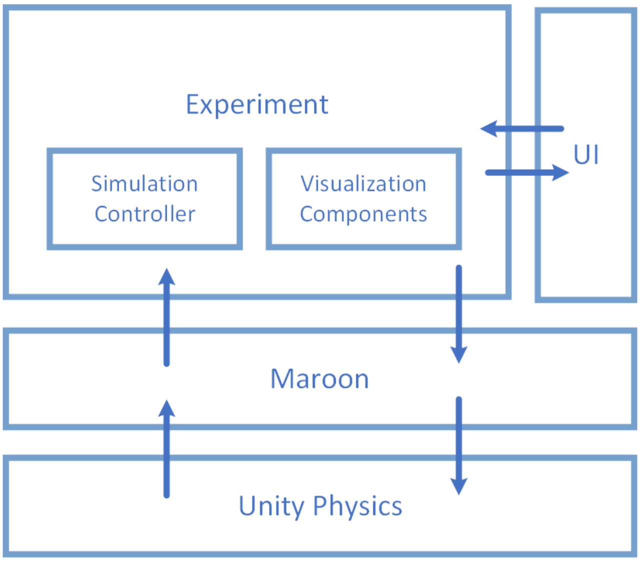

Figure 5.1.: Conceptual architecture with the different components

5.2. User Interface

The User Interface (UI) is designed to allow easy and fast interactions with the experiment environment. There are two different interfaces which support different user interactions:

- **PC UI**: Provides a user-friendly graphical user interface similar to classical computer applications. It contains different panels where the user can configure parameters during runtime. Using the control buttons, the user can start, pause, resume, and reset the simulation.
- **VR UI**: Various virtual control elements allow the user to interact with the virtual world. Sliders on virtual control panels are used to change parameters and visualizations. The simulation can be started, paused, resumed, and reset by three virtual buttons placed in front of the experiment.

Figure 5.2 shows the different user interfaces for PC and VR of the Falling Coil experiment. For the graphical user interface, the Unity UI was used. Unity provides various standard UI elements such as panels, sliders, and

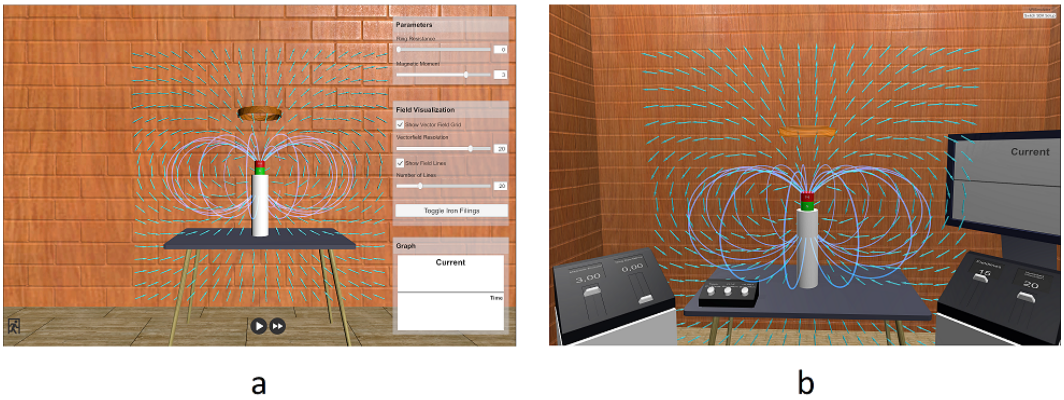

Figure 5.2.: Different user interfaces: a) graphical user interface for PC and b) virtual control elements for VR

buttons. Regarding entering numerical values, sliders are the first choice. The input is fast, uncomplicated, and intuitive. The Unity standard slider allows registering methods which are called if the value changed (Unity, 2019e). This is used to invoke changes to the physical objects. In contrast to the classical mouse control, VR solutions require different interaction methods. The Virtual Reality Toolkit (VRTK) provides different components to interact with virtual objects comfortably. The `VRTK_Slider` allows the user to interact with an object as if it were a slider (VRTK, 2019e). This component is extended to set an invoke object and a method, which is called if the slider has been moved. Both UI variants offer the same functionality to the user, but with a different level of immersion.

The experiments implement the different interfaces in separate scenes but use the same base objects. The base objects are stored in prefabs, which makes it easy to apply changes to all simulations that use it. The following sections describe the different prefab implementations.

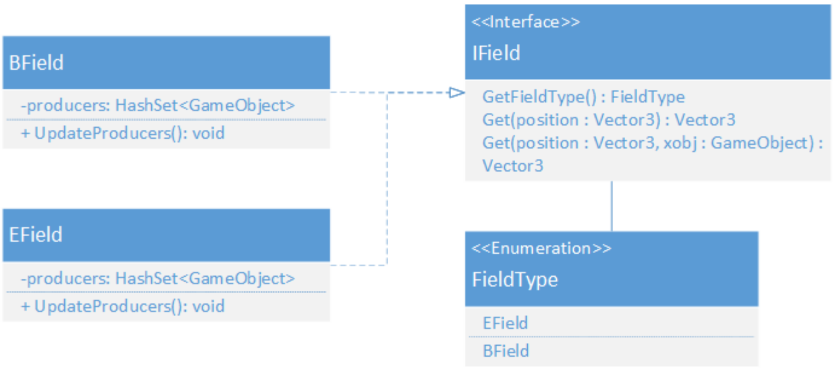

Figure 5.3.: IField interfac UML diagram

5.3. Electromagnetic Fields

An electromagnetic field is a physical field produced by an electromagnetic object. The field can be described as the combination of an electric field (`EField`) and a magnetic field (`BField`). The `IField` interface describes each kind of physical field (see Figure 5.3). It defines a contract that has to be implemented by any physical field. The specific implementations have to take care of calculating the resulting field strength. To determine the total field strength at a position, all producers in the scene must be considered. The field implementations contain a list of all producers used to calculate the resulting field according to the superposition principle. All producers are tagged as “GenerateB” or “GenerateE”, which make it easy to detect all producers that influence the electromagnetic field.

5.3.1. Electromagnetic Objects

The `EMObject` is the base class for electromagnetic objects and is responsible for generating an electromagnetic field, as explained in Section 4.3. Each electromagnetic object is surrounded by a magnetic field which is given by its field strength and the magnetic dipole moment. Recalling the Equation 4.15, the `EMObject` has to calculate the field strength at any given position of the experiment. The `EMObject` implements the `IGenerateB` interface which is required to all producers that generate an electromagnetic field. The forces acting on the object can be activated or deactivated via an additional option. In order to reset the electromagnetic object to its initial state, it has to implement the `IResetObject` interface. Each resettable object has to implement this interface so that the `SimulationController` can reset all experiment relevant objects. The `PausableObject` allows pausing and resuming the simulation at any time. The associations between the different components are shown in Figure 5.4.

For the Falling Coil and the Faraday's Law experiment, two special electromagnetic objects (a magnet and coil) are needed. These two objects are specific implementations of the `EMObject` and will be discussed in the following two sections.

5.3.2. Magnet

The `Magnet` class inherits from the `EMObject` and represents a permanent magnet with a constant magnetic field. It provides additional methods which make it possible to change specific parameters during the simulation runtime. That results in a field change, which affects the simulation. Simultaneous, magnets in the scene exert forces on each other due to their material characteristics. The acting forces are calculated every fixed frame-rate frame and are applied to the object by adding it to the `Rigidbody` component. This component puts the object motion under the control of Unity's physics engine and applies the forces to the object in a physically realistic way (Unity, 2019d).

5.3.3. Coil

The `Coil` class also derives from the `EMObject` and represents an electromagnetic coil as described in the physical fundamentals. It extends the `EMObject` with additional attributes which describe the coil dimensions and the electrical properties. Each coil winding generates its own magnetic field which overlaps with the other windings generated fields. The resulting

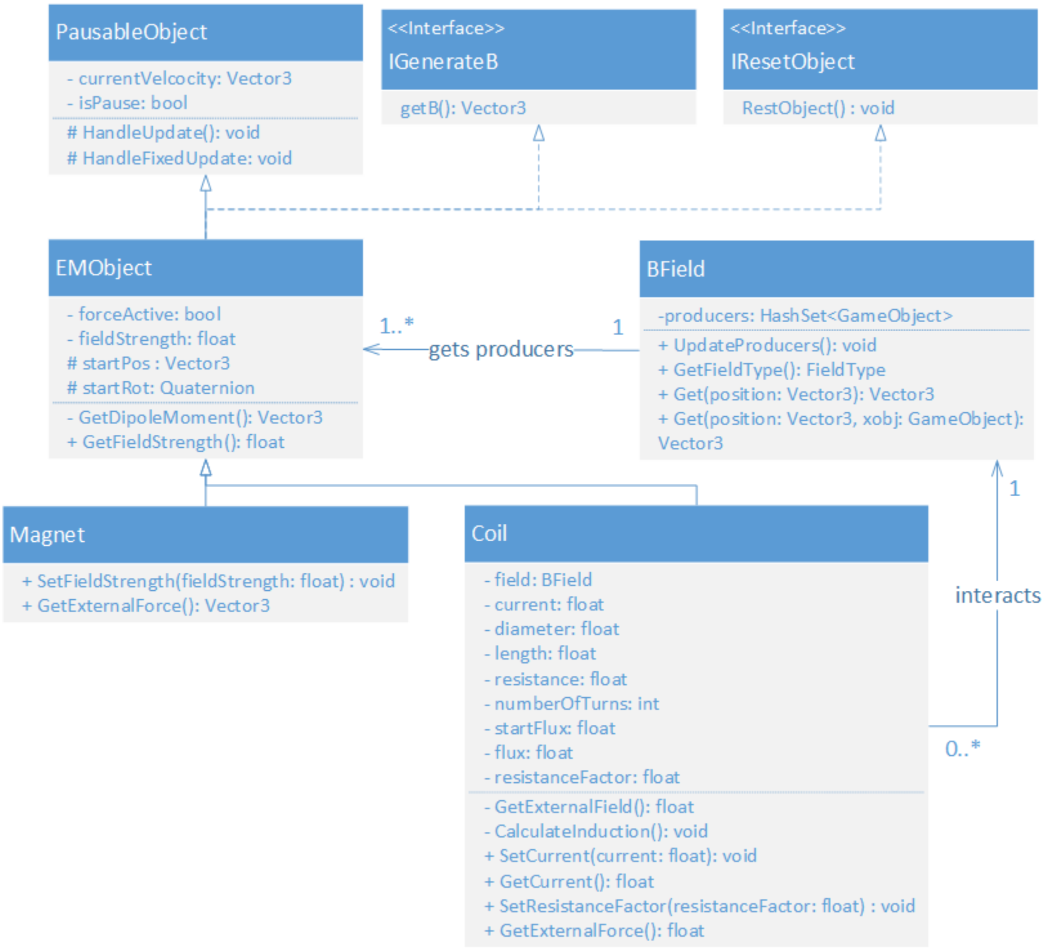

Figure 5.4.: EMObject UML diagram

field strength is calculated according to Equation 4.17. Recalling the electromagnetic induction, the `Coil` has to calculate the induced current in each update. To calculate the actual current, the magnetic flux inside the coil has to be determined. For that, it is necessary to retrieve the field from `BField` without the coil field itself. The magnetic flux is then calculated as shown in Equation 4.19. Similar to the magnet, forces act on the coil. The forces are calculated according to Equation 4.24 and added to the `Rigidbody` component.

5.3.4. Capacitor

The `Capacitor` (see Figure 5.5) consists of two `CapacitorPlates` and the `Dielectic` placed between the two plates. It stores electrical energy in an electrical field which is generated by the capacitor plates. Therefore, the `CapacitorPlate` class implements the `IGenerateE` interface which is required to generate an electric field. In order to calculate the field strength at a given position, the charged plates are divided into infinitesimal pieces. The partial charges are given by

$$\Delta Q = \Delta w \cdot \Delta l \cdot \eta \tag{5.1}$$

where η is the charge density. The field strength is then calculated according to Coulomb's law (see Section 4.1.1). The charge increases proportionally to the voltage. The higher the capacity, the more charge, and energy can be stored. The `Dielectic` component represents the specific dielectric material with its electrical properties and affects the capacity directly. Furthermore, the plate size and the plate distance have an additional impact on the capacity. The `CapacitorPlateController` allows the user to change the plate size via scale handles and to move the plate in the horizontal axis. To get the effective capacitor plate area, the `Capacitor` has to determine the overlapping plate area. For that, the `Capacitor` casts rays from the plate corners in the direction of the opposite plate to check whether the other plate overlaps or not. Algorithm 1 shows the pseudo code of the implemented algorithm.

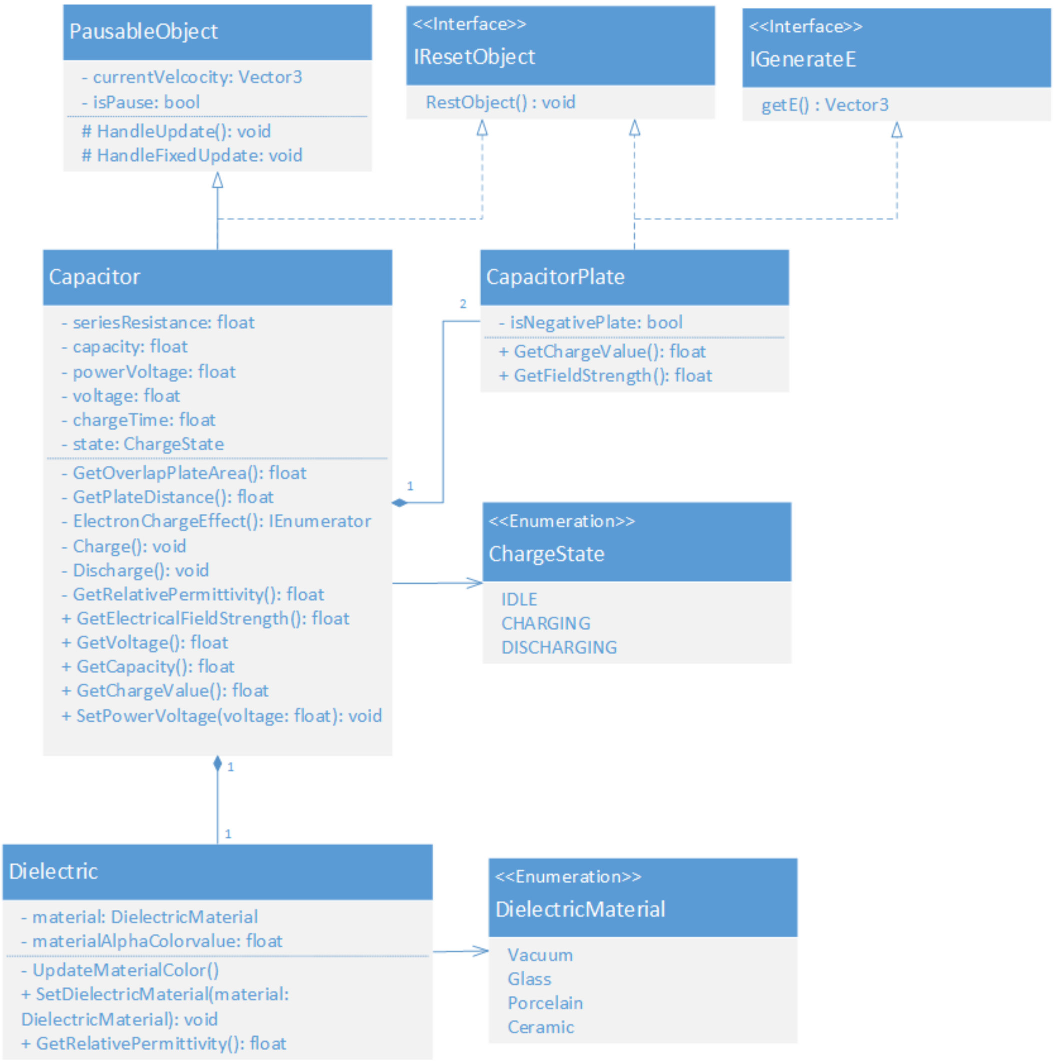

Figure 5.5.: Capacitor UML diagram

Algorithm 1: Calculation of the overlapping plate area

```
Input: $plateA$                         // Positive capacitor plate
Input: $plateB$                         // Negative capacitor plate
Function GetOverlappingArea($plateA$, $plateB$):
    $overlapWidth = 0$
    $overlapHeight = 0$
    $widthCorner$ = $plateA.position$ + Vector($plateA.width/2, 0, 0$)
    $heightCorner$ = $plateA.position$ + Vector($0, plateA.height/2, 0$)
    $testDirection = plateB.position - plateA.position$
    if CheckIfPlatesOverlap($widthCorner, testDirection, plateB$) then
        $overlapWidth = plateA.width$
    end
    else
        $overlapWidth = plateB.width$
    end
    if CheckIfPlatesOverlap($heightCorner, testDirection, plateB$) then
        $overlapHeight = plateA.height$
    end
    else
        $overlapHeight = plateB.height$
    end
    return $overlapWidth * overlapHeight$

Function CheckIfPlatesOverlap($cornerPoint$, $testDirection$, $plate$):
    $hit$ = RaycastHit()
    if Raycast($cornerPoint, testDirection, hit$) then
        if $hit = plate$ then
            return $true$
        end
    end
    return $false$
```

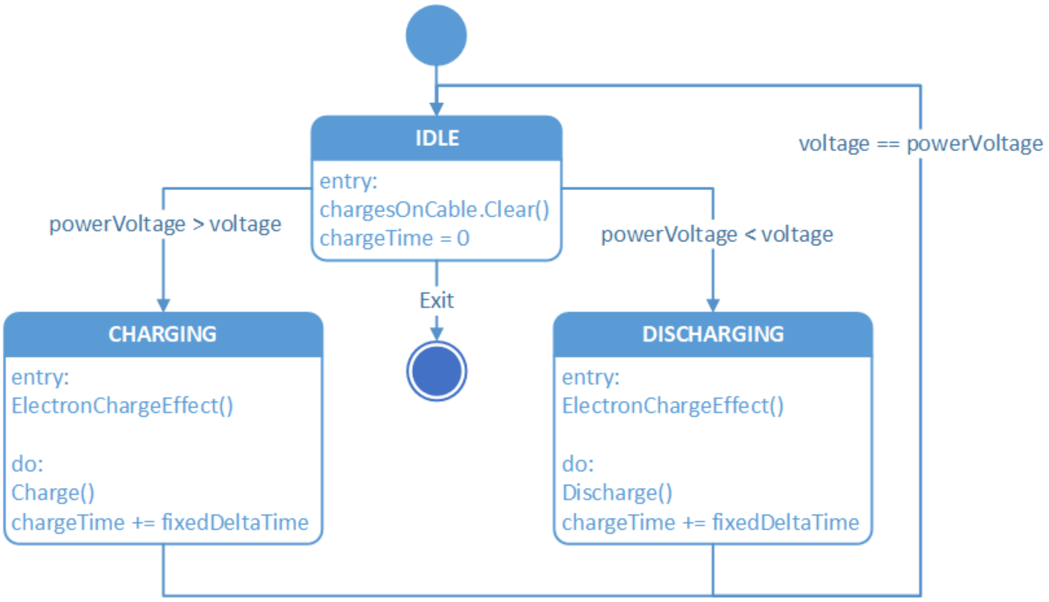

Figure 5.6.: Capacitor state machine

When the simulation starts, the capacitor charges or discharges to the given power voltage. At the beginning of the simulation, the `Capacitor` is in the IDLE state. If the power voltage is higher than the capacitor voltage, it enters the CHARGING state and charges the capacitor. Otherwise, it enters the DISCHARGING state and discharges the capacitor. It returns to the IDLE state once the capacitor voltage has reached the value of the power voltage. Figure 5.6 shows the corresponding state diagram including states and transitions. Further details are described in Section 4.2 using the equations 4.12 and 4.14.

5.4. Wave Propagation

Recalling Section 4.4.1, the wave propagation within a medium takes place through the stimulation of particles to move due to already oscillating particles. In the experiment scene, the `WaveGenerator` (see Figure 5.7) is responsible for generating a wave at a given position. It specifies the amplitude, frequency, wavelength, and propagation mode. Additionally, it returns the wave deflection at a specific position at a given time. Since there can be several wave generators, the `WaveGeneratorPoolHandler` holds a reference of all generators to apply property changes to all of them or only to a specific generator. Each generated wave propagates from a certain position and overlaps with the other waves. The `WaterPlane` represents the propagation medium and calculates the interferences according to the superposition principle. Depending on the resulting wave values, the mesh vertices are manipulated in their y-coordinates to create a three-dimensional wave object (see Algorithm 2). In order to calculate the diffraction at a slit plate, it is necessary to determine whether a vertex is in front of or behind the plate. Therefore, a ray is cast from the wave origin in the direction of the vertex. If the ray cast hit the plate, the vertex is located behind the plate, otherwise in front of the plate. Figure 5.8 shows a double slit plate including the wave generators and the resulting interference pattern.

Algorithm 2: Updating water plane vertices

```
Input: $planeMesh$                // The mesh of the water plane
Function UpdateWaterPlane($planeMesh$):
    $waveVertices = planeMesh.vertices$
    for $i \leftarrow 0$ to $waveVertices.length - 1$ do
        $waveVertex = waveVertices[i]$
        $waveVertex.y$ = GetTotalWaveValue($waveVertex$)
        $waveVertices[i] = waveVertex$
    end
    $planeMesh.vertices = waveVertices$
    $planeMesh$.RecalculateBounds()
```

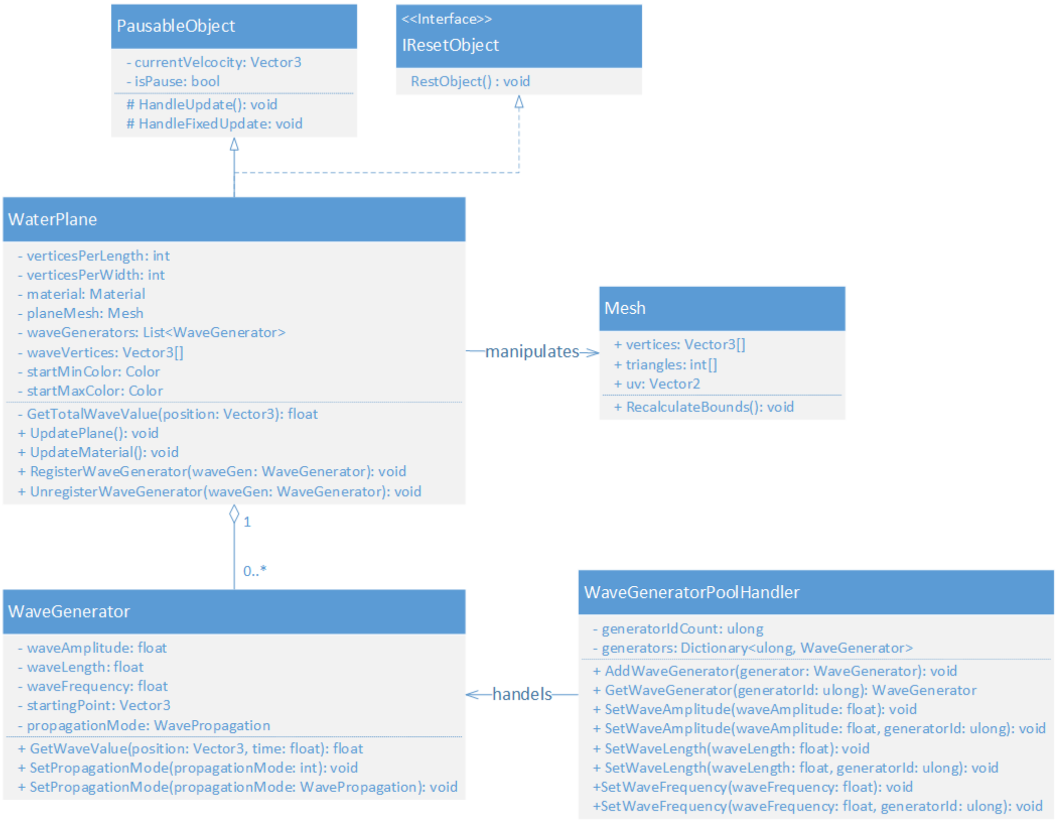

Figure 5.7.: WaveGenerator UML diagram

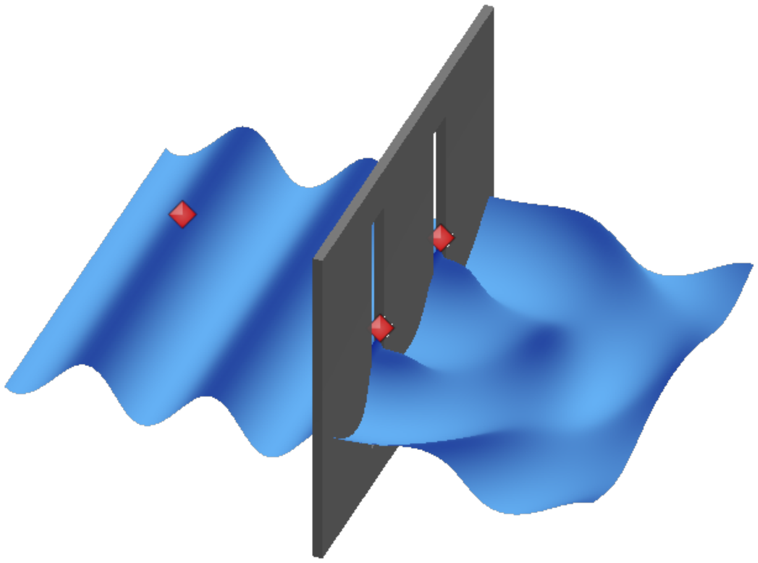

Figure 5.8.: Double slit with waves generators (red points)

5.5. Visualizations

Quite often, theoretical knowledge and formulas are not sufficient to understand complex physical concepts. Physical phenomena such as induction or magnetism are easier to understand if they are visible. This section describes the different visualizations used to illustrate the underlying physical phenomena to improve conceptual understanding.

5.5.1. Vector Field

The `VectorField` class allows visualizing a physical field of the type `IField`. Multiple arrows, aligned in a grid, show the physical field and are updated every frame. Each field arrow is rotated during the `Update`-method according to the field vector at the arrow position. The arrow scale and the position depending on the vector field resolution (number of arrows per

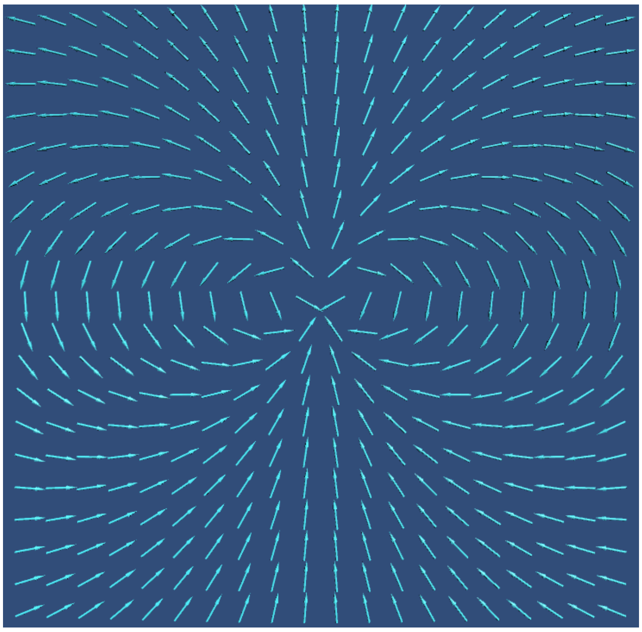

Figure 5.9.: Vector field of a permanent magnet

row/column). The `VectorField` instantiates and arranges the field arrows according to the vector field resolution in the grid. Figure 5.9 shows the vector field of a permanent magnet. The `VectorField` component is used in the Falling Coil and the Faraday's Law experiment as well as in the Capacitor experiment to show the underlying physical field.

5.5.2. Iron Filing

The `IronFiling` allows the static visualization of a physical field of the type `IField`. It mimics iron filings, which arrange themselves along the field lines as described in Section 4.3.4. In order to create such a field image, a set of `LineRenderer` are used. The `LineRenderer` component takes an array of two or more points and draws a line between each point (Unity, 2019c). Each iron filing line starts at a random position and draws a certain segment length in the direction of the field. From the reached position the drawing is repeated along the field until the boundary or the maximum of vertices is

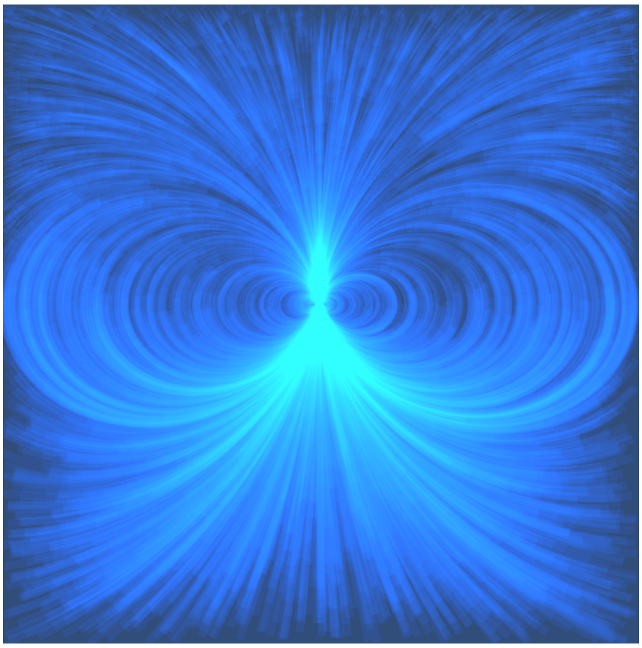

Figure 5.10.: Iron filling visualization of a permanent magnet

reached. All lines together, in combination with a particle material, result in the desired image. Due to the randomly chosen starting points of the lines, the result will always be slightly different. An example of the result of an iron filing visualization outcome is shown in Figure 5.10. It shows the magnetic field of a permanent magnet. The `IronFiling` component is also used in the Falling Coil, Faraday's Law, and Capacitor experiment to visualize the generated field.

5.5.3. Field Line Manager

The `FieldLineManager` (see Figure 5.12) is used to manage the field lines of electromagnetic objects. It holds a reference to all field lines and updates them in every frame. Since the field lines of a magnet or a coil are symmetrical around the object, it is not necessary to recalculate all field lines around the symmetry axis. The `SymmetricFieldLineManager` extends the `FieldLineManager` class and copies each field line around the symmetry axis instead of drawing it repeatedly. Figures 5.12 shows the symmetric field lines of a permanent magnet. In contrast to the symmetric field lines, the field lines of a capacitor pass from one plate to the other (see Figure 5.13). For that, the `CapacitorFieldLineManager` instantiates multiple field lines and draws each line for itself.

The `FieldLine` class is responsible for drawing the line. It uses a `LineRenderer` to connect multiple vertices to a field line. When a field line starts drawing, it starts at the origin of the electromagnetic object. However, to avoid excessive field effects inside the electromagnetic object, an offset is added to the line's starting point. From this point, the field draws a certain line segment length in the direction of the field vector. From the reached position the drawing is repeated until a stopping criterion is reached. For example, this can be a closed field line or the contact with a certain object.

5.5.4. Capacitor Charging/Discharging

When the capacitor is charging or discharging, its process is visualized by moving charges. The charges start moving when the `Capacitor` enters the respective state (CHARGING or DISCHARGING). The number of moving charges depends on the difference between the capacitor voltage and the power voltage. The charges follow the cable from one capacitor plate to the other plate. If the capacitor is charging, the charges are moving from the positive plate to the negative plate. Otherwise, the charge movement is reversed. The charge's path is defined by the cable which connects the capacitor plates with the power voltage. The cable consists of several small capsules which are connected by a joint (see Figure 5.14). The `Joint` component connects two objects and enables a constrained motion (Unity, 2019b). In order to follow the cable path, the charges will move from capsule to capsule until it reached the end of the cable.

5.5.5. Graph

The `Graph` component is used to display a measured value over time. It takes an object of which the value should be displayed and a getter method

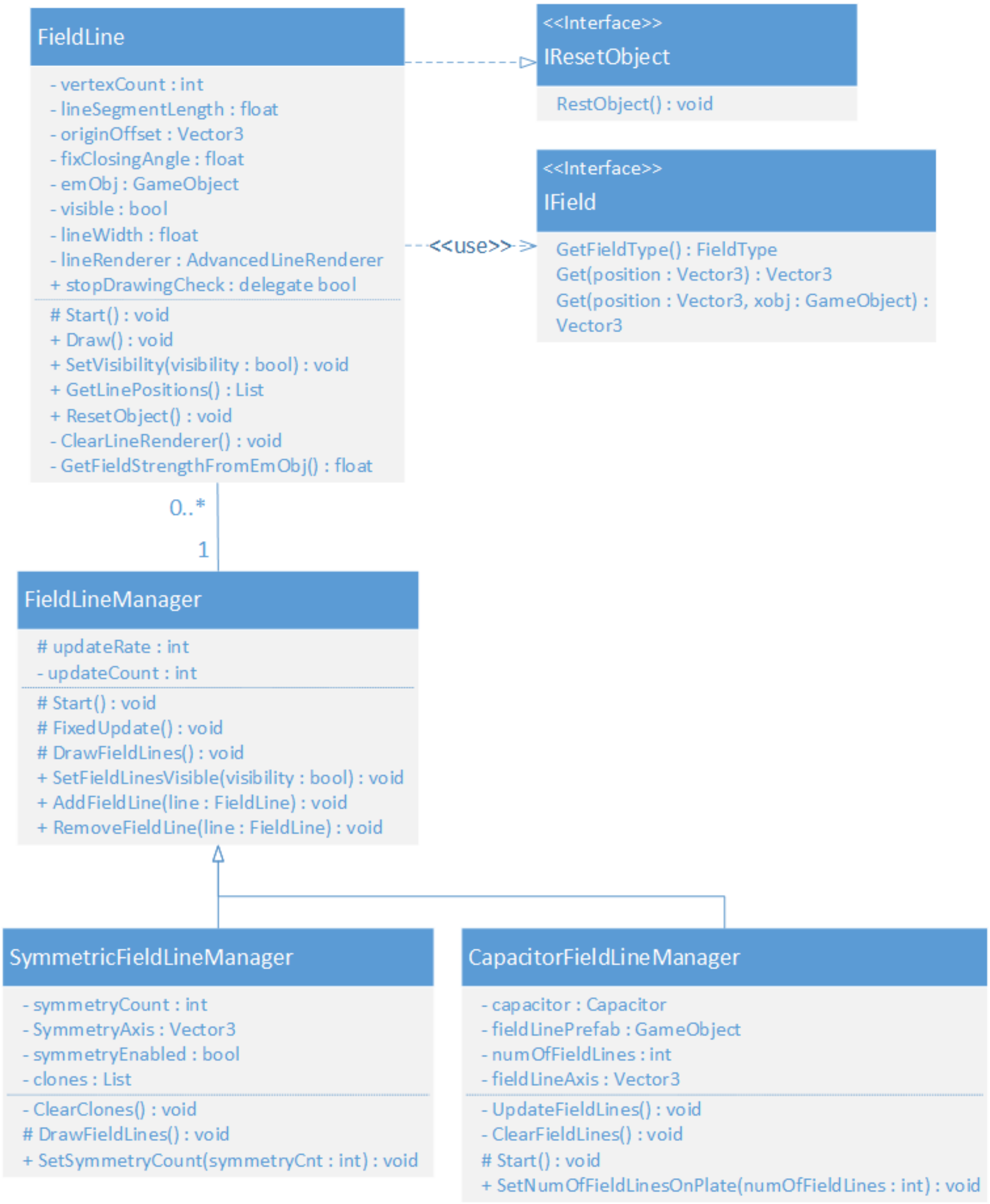

Figure 5.11.: Field Line Manager

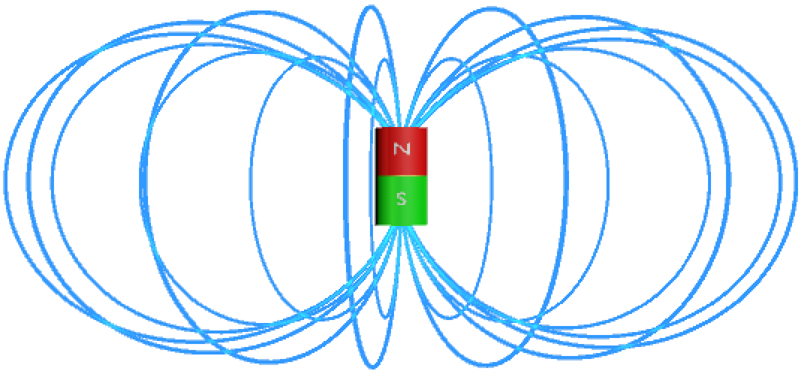

Figure 5.12.: Symmetric field lines

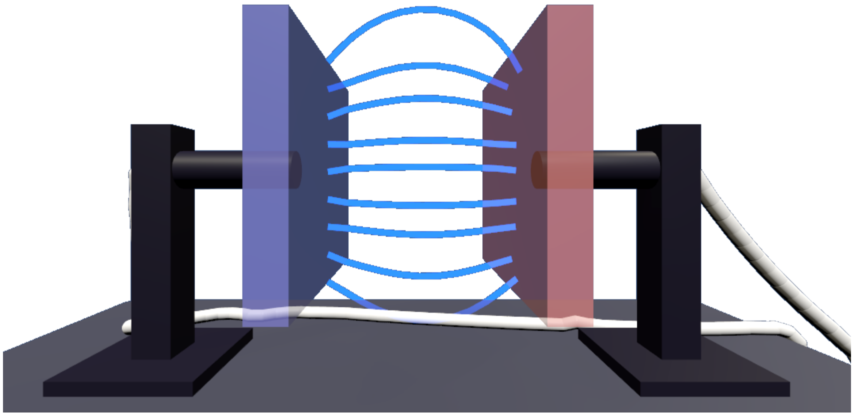

Figure 5.13.: Capacitor field lines

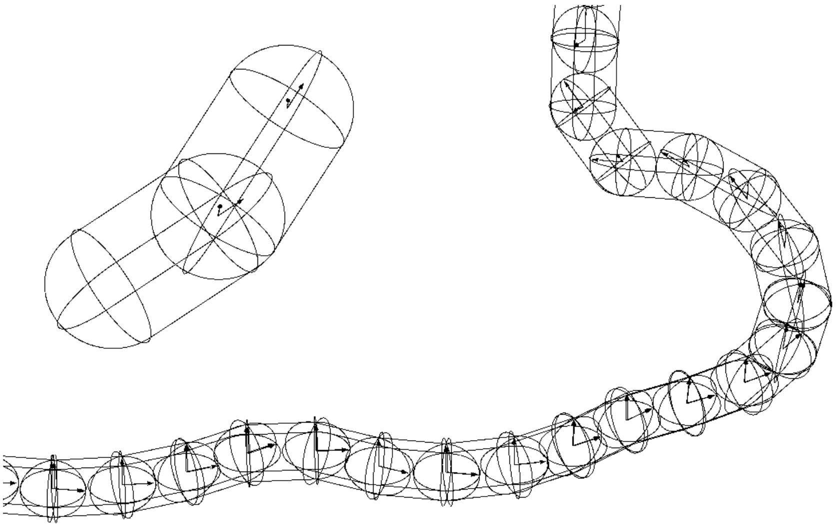

Figure 5.14.: Cable

to receive the current value from the given object. In each fixed update, the current value is obtained and displayed in the graph. Since the Unity `LineRenderer` does not support adding vertices after drawing, a wrapper is used to redraw the line in every frame. Figure 5.15 shows the different graph draws for the PC and VR variant. It displays the induced current of a coil in a magnetic field.

5.5.6. Wave Visualization

In order to visualize waves, a water-filled basin is used. The `WaterPlane` generates a customized plane with a specific number of vertices. A sufficiently high number of vertices allow for a smooth wave representation. Each vertex is changed according to the wave deflection in the y-coordinate. Figure 5.16 shows the generated mesh for a circular wave. For wave coloring, a special water surface shader interpolates between two wave colors to produce a wave image. The `ColorMax` and the `ColorMin` property are the corresponding values for a wave peak respectively for a wave trough. This two colors can be changed by the user to obtain a better visible interference pattern.

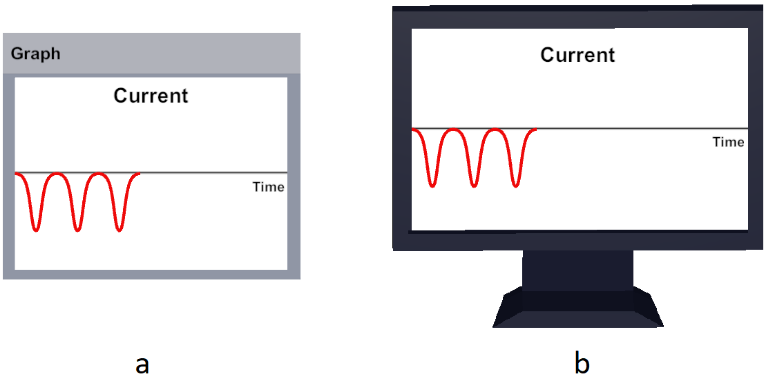

Figure 5.15.: Graph: PC panel(a) and VR screen(b)

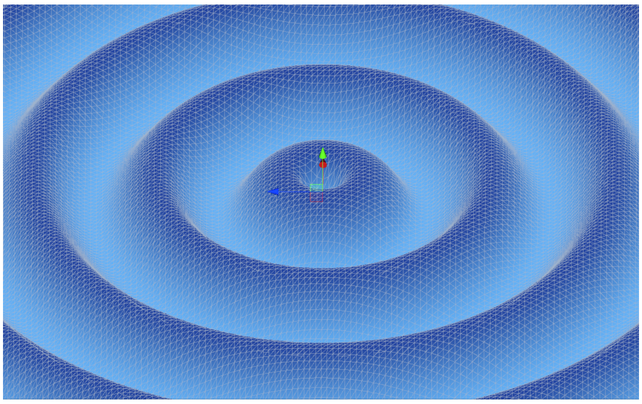

Figure 5.16.: Circular wave mesh

5.6. Summary

This chapter described the implementation of the physical components and the visualizations of the implemented experiments. Each experiment is based on the physics engine and is controlled by the simulation controller. The specific user interfaces enable the user the direct interaction with the experiment. User changes are directly invoked to the corresponding object and influence the experiment outcome.

The `EMObject` represents the base class for each electromagnetic object and is responsible to calculate the field at a given position. Specific implementations of this object are the `Magnet` and the `Coil`. They generate a magnetic field (`BField`). The `Capacitor` generates an electric Field (`EField`) based on Coulomb's law. To illustrate the underlying physical concepts there are different visualizations. Using vector field arrows, iron filing lines or field lines allows observing the physical field.

The wave propagation is done via a custom plane with numerous vertices which are manipulated by wave generators in the scene. Each generator propagates from a certain point and effects the vertices in their y-coordinate. A special water surface shader interpolates between two wave colors and colors the plane depending on the vertex values. The next chapter deals with the evaluation of the implemented experiments.

6. Evaluation

To evaluate the effect of immersion using virtual reality, an A/B split user study with 20 participants was performed. The goal of this study was to compare the two different variants of Maroon (Maroon VR and Maroon PC) to identify advantages, disadvantages, and application scenarios.

The research focus of the study was on:

- Engagement
- Immersion
- Learning Experience
- Usability
- User Experience

This chapter is mainly based on the previous publication of Pirker, Holly, et al. (2017).

6.1. Material and Setup

For conducting the study, a high-performance computer with two NVIDIA GeForce 960 GPUs in SLI mode was used. The Maroon PC setting included a classical PC workstation with a monitor, mouse, and keyboard. For the Maroon VR setting, we used the HTC Vive in a 2m x 2m area. The HTC Vive allows the user to move in the defined area while wearing a VR headset and interacting with two controllers. The two base stations track the position and motion and transfer it into the virtual world.

6.2. Method and Procedure

The study was set up as an AB/BA test. It is a test method to evaluate two versions of a system. For testing, we split the participants into two groups. The participants in the first group started with Maroon VR and the second group with Maroon PC. Afterwards, the groups were swapped, so that the participants using the VR version were now using the PC version and vice versa. Before the user test started, each participant was asked to fill out a pre-questionnaire. In the questionnaire, the proficiency about their computer, VR, and video game experience was collected as well as demographic information. In the beginning, each participant received a short introduction on how to interact with the different system settings. They learned to move in room-scale VR and to use the Vive controllers to interact with virtual objects such as sliders. Furthermore, they were familiarized with the PC controls to interact with the Desktop variant. During the test, users had to perform the following tasks:

1. Look around in the lab environment for two minutes and get a first impression.
2. Go to the falling coil experiment and start the simulation. Try to identify the relationship between the magnetic field and the electrical current. Use the iron filing to illustrate the magnetic field.
3. Go to the Faraday's Law experiment and start the simulation by moving the magnet towards the coil. Try to understand the acting force on a current-carrying conductor.
4. Take time and look at the rest of the lab environment.

At the end of each experiment, the participants were asked about the physical concepts to measure their learning outcomes. For measuring, the following questions were asked:

1. Falling Coil: What is the relationship between the magnetic field and the electrical current?
2. Faraday's Law: Which quantities determine the force effects for a current-carrying conductor in a magnetic field?

After answering the physics question, participants were asked about their confidence in the correctness of the answer. After the completion of all tasks, the participants were interviewed about their impressions. When the users had finished all tasks, they were asked to answer a post-questionnaire. They had to answer ten open-ended questions about their impression of the environment, 20 questions on a Likert scale between 1 (fully disagree) and 7 (fully agree) regarding their sentiment towards the physics lab, and 19 questions adapted from the Game Engagement Questionnaire (GEQ) (Brockmyer et al., 2009) to measure engagement, flow, presence, and immersion with rations on a scale between 1 (not at all) and 5 (extremely). Finally, each participant had to fill out a general post-questionnaire about the completed experiments.

6.3. Participants

Twenty participants aged between 20 and 28 (AVG=24.05, SD=2.31) tested the different laboratory environments for PC and VR. Eleven participants started with Maroon VR and used the PC version in the following session. The remaining participants performed the test in reverse order. Of the participants, 18 were students and two employees. At the time of the evaluation, most of the students were studying computer science. Four participants had a background in industrial design, mechanical engineering, and business administration. Twelve participants rated themselves as an advanced computer user (AVG=4.4, SD=0.82), eleven ranked themselves as experts in video-games (AVG=4.2, SD=1.06), and 18 liked playing video games. None of them are very experienced with VR (AVG=1.65, SD=0.81). However, 18 participants had already heard of it, and eleven had tried it before. Of those who had previously used a VR device, two had tried the HTC Vive before. There were only two who had experience with cyber sickness. None of the participants think of themselves as an expert in physics. The following section discusses the results of the questionnaires and the interviews.

6.4. Results

The learning outcome depends mainly on the user experience and the acceptance of the system. To identify the strengths and weaknesses of the system, users were asked about their preferences and dissatisfaction during the experiments. Furthermore, they were asked about their learning experience. The results consist of open-ended answers, in the form of text input and answers based on a Likert scale.

6.4.1. Experience, Immersion and Engagement

Most of the participants reported that the VR room-scale variant was much funnier (AVG=6.1, SD=1.5) compared to the PC version (AVG=4.9, SD=1.8). They described the VR lab experience as "*more cool and more fun because one can touch everything*". When they were asked about motivation and engagement, most of them found that the two learning environments are the same, but more motivating in VR. One of the most given answers to the question "What did you like?" was immersion and the ability to interact with objects. As seen in table 6.2, immersion was much more intense in the VR version than in the PC version. Some of the users were so immersed that they lost track of time. Presence, absorption, and flow were also perceived much higher in VR (see Figure 6.1). One participant described it as "*interesting to play with the experiments in a virtual space integrated into the personal vision. It feels much more part of the real world and as if oneself has an impact on the experiments*". Another participant mentioned that a step by step guide is missing in the PC version, but prefers to try different things in VR by its own. In general, the VR experience was described as more attractive (AVG=6.0, SD=1.3) compared to the PC variant (AVG=5.3, SD=1.3). Table 6.1 shows the whole results of the Game Engagement Questionnaire.

		Maroon VR		Maroon PC	
GEQ Statement	Category	AVG	SD	AVG	SD
I lose track of time	Presence	3.5	1.6	2.3	1.4
Things seem to happen automatically	Presence	2.6	1.2	2.4	1.5
I feel different	Absorption	2.7	1.6	1.4	0.7
I feel scared	Absorption	1.1	0.3	1.1	0.2
The game feels real	Flow	3.3	1.0	1.7	0.9
If someone talks to me, I don't hear them	Flow	1.2	0.5	1.3	0.6
I get wound up	Flow	1.8	1.1	1.6	0.9
Time seems to kind of stand still or stop	Absorption	2.3	1.4	1.3	0.6
I feel spaced out	Absorption	3.0	1.3	1.4	0.7
I can't tell when I'm getting tired	Flow	2.1	1.3	1.7	0.9
Playing feels automatic	Flow	3.1	1.3	2.3	1.4
My thoughts go fast	Presence	2.8	1.5	2.3	1.5
I loose track of where I am	Absorption	3.2	1.5	1.5	0.8
I play without thinking about how to play	Flow	3.5	1.5	2.7	1.6
Playing makes me feel calm	Flow	2.8	1.5	3.1	1.6
I play longer than I mean to	Presence	3.4	1.4	1.9	1.1
I really get into the game	Immersion	3.7	1.1	2.2	1.1
I feel like i just can't stop playing	Flow	2.4	1.0	1.6	0.8
I don't answer when someone talks to me	Flow	1.2	0.5	1.1	0.2

Table 6.1.: Detailed comparison of GEQ elements between Maroon VR and Maroon PC based on a Likert scale between 1 (not at all) and 5 (extremely) (adapted from Pirker, Holly, et al., 2017)

	Maroon VR		Maroon PC	
Category	AVG	SD	AVG	SD
Presence	3.0	1.4	2.2	1.4
Absorption	2.5	1.2	1.3	0.6
Flow	2.4	1.1	1.9	1.0
Immersion	3.7	1.1	2.2	1.1

Table 6.2.: Comparison of GEQ main elements between Maroon VR and Maroon PC (adapted from Pirker, Holly, et al., 2017)

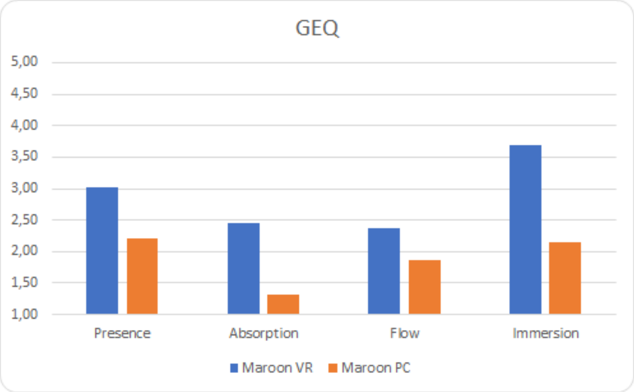

Figure 6.1.: GEQ results comparing average between Maroon VR and Maroon PC version (adapted from Pirker, Holly, et al., 2017)

6.4.2. Usability and User Experience

While most participants had no issues with the HTC Vive controls, others needed a short time to get familiar with the controls. In contrast, none of the participants had any problems with the PC controls (mouse and keyboard) since it was similar to classic computer games. Users described it as more useful to get an overview of the experiments. However, the interaction in VR were perceived as more realistic and natural. Therefore, many users would prefer the interaction in VR even if it is not familiar.

Each user started in the main laboratory room which was designed as an three-dimensional menu. Several participants found the lab room too large and had an issue with the scaling. Furthermore, the placement of objects was also rated as sub-optimal. A user described the lab as *"a prison (very tall walls, no windows, a metal door); it looks not very friendly"*. Users have positively mentioned the realistic elements in the lab environment. For example, the working clock on the wall was repeatedly noticed by users.

6.4.3. Learning Experience

After each session, participants were asked about their learning experiences. Users rated both lab variants as positive and would like to learn with Maroon, but prefer the VR environment. The participants described it as more engaging to see physics simulations with VR glasses than without. Most of the participants rated learning in VR as more fun (AVG=6.1, SD=1.5) than in the PC version (AVG=4.9, SD=1.8). In general, they found that the lab makes the content more interesting and easier to understand. When interviewing the participants, many users mentioned the experimentation and visualization of invisible phenomena positively: *"I liked the field lines and the different options in the experiments such as pausing to get a more accurate impression or to study the field lines in detail."* They found that elements such as field lines are easier to see on a screen, but described the VR version as more effective because they would spend more time learning the content with a higher focus on it. The haptic feedback through the controller as an additional dimension made it easier for users to understand the force effects in the magnetic field. Users also mentioned that they would prefer Maroon in a classroom with additional information. Users thought: "*For a better understanding, it needs more information about the results or the experiments in the rooms.*" However, they would rather use the VR version at home than the PC version. More details about the learning experience are shown in Table 6.3.

In order to measure the learning outcome, participants were asked about the physical phenomena they had experienced in the experiment rooms. After answering the physics question, participants had to rate themselves on a scale between 1 (not at all) and 5 (very) how sure they are about their given answer. While many participants reported that they learned better with the PC version, it seems that they gained a better understanding by using the VR version. 18% of the VR users were able to describe the relationship between the magnetic field and the electric current correctly, and 36% almost correctly. After performing the same experiment in the PC version, only 33% of the PC users described the phenomenon almost correctly (see Figure 6.2). The second phenomenon was described by 18% of the VR users completely right, and by 82% almost right. In contrast, none of the PC users could describe the force effects of a live conductor in a magnetic field. Only 78% were able to describe it almost correctly (see Figure 6.3). In both variants, participants were not sure about the correctness of the given answers.

6.4.4. Limitations

The results of this study should help to learn more about motivation, immersion, and engagement, but were limited to a small number of participants. However, the outcomes give a good overview of the potential of both learning environments. Furthermore, they raise new research questions in learning behaviours to get a better understanding of differences in learning. Both experiences can have different impressions of several forms of learning concepts. Understanding how students learn and which concepts are useful for which experience is essential for learning.

	Maroon VR		Maroon PC	
Statement	AVG	SD	AVG	SD
I would like to learn with the Physics Lab	5.3	1.8	5.0	1.6
It is a good idea to use the Physics Lab for learning	6.0	0.9	5.6	1.0
The Physics Lab is a good supplement to regular learning	5.6	1.4	5.4	1.4
I learned something with the Physics Lab	4.1	1.6	4.4	1.8
The Physics Lab makes the content more interesting	6.0	1.3	5.3	1.3
The Physics Lab makes the content easier to understand	4.9	1.8	5.3	1.7
The Physics Lab makes learning more engaging	5.7	1.6	5.7	1.2
The Physics Lab makes learning more fun	6.1	1.5	4.9	1.8
The Physics Lab makes learning interesting	6.0	1.2	5.3	1.3
The experience with the Physics Lab inspired me to learn more about physics	4.0	1.9	4.1	1.8
Learning with the Physics Lab was more motivating than ordinary exercises	5.6	1.5	5.1	1.5
It makes course content more interesting to learn about	5.4	1.6	5.0	1.5
I would rather like to learn Physics with the Physics Lab than with traditional methods	5.0	1.7	4.5	1.7
I find regular physics classes boring	4.8	1.9	5.1	1.8
I would like to learn with the Physics Lab at home	5.0	1.6	4.4	2.1
I would like to learn with the Physics Lab in the classroom	5.6	1.7	5.2	1.4

Table 6.3.: Learning Experiences in Maroon VR and Maroon PC rated on a Likert scale between 1 (fully disagree) and 7 (fully agree) (adapted from Pirker, Holly, et al., 2017)

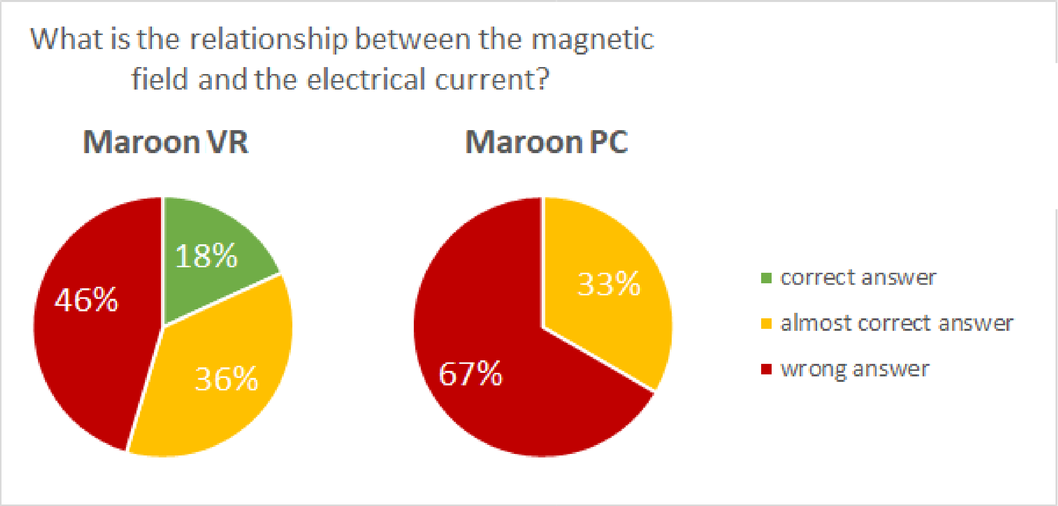

Figure 6.2.: Distribution of the answers according to their correctness to the question "What is the relationship between the magnetic field and the electric current?"

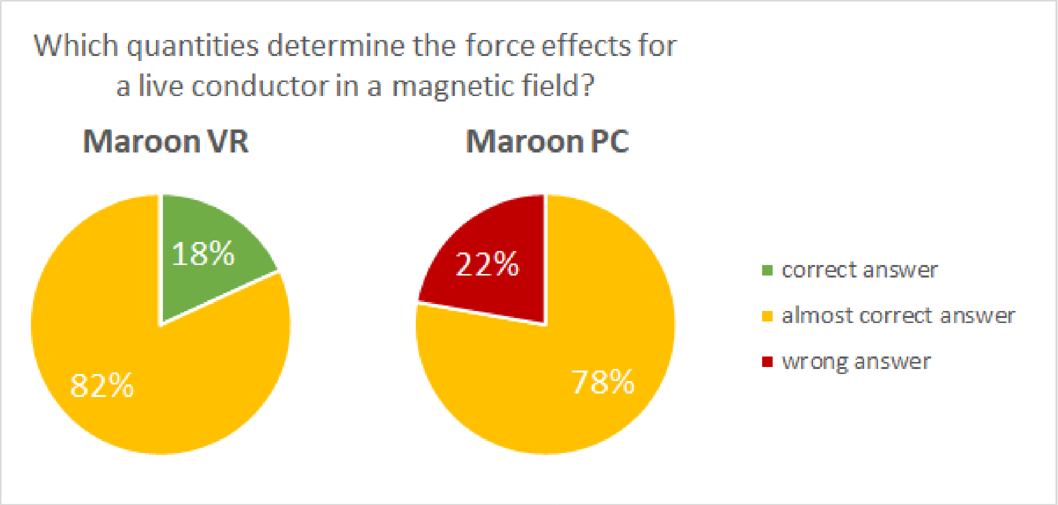

Figure 6.3.: Distribution of the answers according to their correctness to the question "Which quantities determine the force effects for a live conductor in a magnetic field?"

6.5. Discussion

Maroon was described as a very engaging and immersive environment for learning physics. The results show that such an interactive and immersive experience has a great potential to change guided learning in classrooms and self-regulated learning at home. The participants would prefer the laboratory as a supplement to traditional classroom learning where they get additional information about the physical concepts. The evaluation of the two learning environments showed that the VR experience was received as more engaging and immersive than the PC version. Interactive and realistic objects enhance the feeling of immersion.

When the participants were asked about the physical concepts, the VR users were able to answer the questions much better than the PC users. VR also enhanced the concentration of the participants on the experiments. The PC version, in contrast, offers an easier way to read and view learning content such as written concepts or field lines. The participants suggest the PC version with step-by-step instructions, while in VR the explanatory approach was favoured. Thus, the VR lab could be used as a self-directed learning tool after class. Although the results were limited to a small number of participants, the results show the potential of the two learning environments and raise new research questions which should be considered in future studies.

In conclusion, Maroon makes learning content more interesting and easier to understand. It helps students to see invisible phenomena by providing different visualizations. While the VR variant is an interesting and new way to learn, the PC version is more familiar and gives a better overview. Although the interaction with the lab was received very positively, there is still potential for improvement, especially in learning and usability.

7. Lessons Learned

This chapter discusses the findings during the literature research, the design and development phase, and the evaluation. The gained insights will be included in the following chapter for possible improvements and future work.

7.1. Theory

In retrospect to the theoretical part of this thesis, various learning techniques with high potential in increasing students' motivation and engagement were presented. It has been shown that active learning is a powerful teaching method which involves students directly in the learning process. Learning techniques such as interactive simulations, visualizations, virtual or remote laboratories have various benefits for learners, but also different drawbacks and limitations which need to be considered when designing such tools. For instance, it is still a challenge to maximize the fun of learning and to motivate students to learn in the first place. Virtual reality has proven to be a useful technology for educational institutions to enhance students engagement and motivation.

7.2. Development

Designing virtual physics experiments to motivate students in learning physics is a challenging task and requires thoughtful design decisions. Insufficient acceptance and motivation impairs the learning experience and can result in a rejection of the learning environment. In order to overcome these issues and to increase the student's enthusiasm in physics, specific design elements have to be used.

Unity proved to be a powerful tool to create interactive and immersive physics experiments. The SteamVR as well as the VRTK plugin were helpful tools to integrate the experiment scenes into a virtual reality environment. Besides the useful features provided by the engine and the plugins, it was quite difficult to build a user interface for different platforms. For instance, it is very time-consuming to build panels in Unity, which contain elements in a correct scaling. The design decisions, as mentioned in Chapter 3, turned out to be an effective way to overcome this issues. The decision to store experiments with all its components as a reusable asset facilitated the integration of the different user interfaces and also makes it easier to extend the experiments for upcoming platforms.

7.3. Evaluation

The evaluation of the system was based on standardized questionnaires which proved to be very effective to measure engagement, flow, presence, and immersion as well as the sentiment towards the physics lab. The combination of questionnaires and open-ended questions gave us a deep insight into users' emotions, preferences, and dissatisfactions. The study was performed as an AB/BA test and allowed a subjective comparison of the two lab variants, independent of perspective but with a focus on the user target group. It turned out to be very useful to compare the different user interfaces with each other. The questions and comments during the experiments helped in finding ideas for further improvements. Future evaluation should make use of more pedagogical questions to get a better understanding of differences in learning and which concepts are useful for which experience.

8. Future Work

The goal of this thesis was the design and implementation of interactive and engaging physics experiments in a virtual laboratory environment. The evaluation showed, that the experiments and the lab environment have a high potential in learning, but still need improvements. The main aspects for future work will be additions, extensions and quality assurance of the existing system.

Currently, the laboratory environment consists of only a few specific experiments in the field of electrostatics, electromagnetism, and wave propagation. Since physics involves much more than these areas, the laboratory should be extended by further experiments involving different physical phenomena. Furthermore, the lab can also be adapted by additional disciplines such as chemistry or computer science. Once further experiments have been implemented, it will be necessary to split the laboratory into different domain areas and configurations. Therefore, it will be useful to create the lab environment procedurally. A streaming mode should provide a guided learning experience where one person demonstrates the experiment while the others are watching. To make it more accessible for schools, it seems appropriate to port the current framework for mobile devices. Students should be able to use their smartphones to enter the laboratory, run the experiments, or follow the teacher's instructions. In order to enable collaborative learning, it will be necessary to extend Maroon with social interaction which allows students to work together on experiments and learn from each other. By providing an interface, an assessment system could interact with the environment and give feedback to students and make their learning progress accessible to teachers.

In order to increase usability, maintainability, and extensibility, the following tools and technologies should be considered in the future:

- **OpenXR**[1] is a royalty-free standard that is intended to facilitate and standardize cross-platform development of virtual reality (VR) and augmented reality (AR) applications - also known as XR. It consists of an application interface and a device plugin interface which enable the development of applications for various platforms such as SteamVR, Oculus, Samsung GearVR, or Windows Mixed Reality and the interaction of different hardware devices (Khronos, 2019). The migration to this standard will simplify the development of Maroon and allows to support a high number of platforms without having to port or re-write the code. Figure 8.1 shows a suggestion for integrating OpenXR into Maroon.

- **UXML** is an upcoming UI format, supported in future Unity releases, which allows developers to define user interfaces in a logically structured form and the definition of large user interfaces by using elements from another UXML file. The Unity-specific style sheets (USS), inspired by the CSS standard, which separates formatting and content and allows the specification of style elements. The query system UQuery, similar to jQuery, provides methods to address elements in the UI hierarchy (Unity, 2019f). This new UI system will help to build reusable user interfaces for Maroon PC.

- **VRTK Interaction Helpers**: The VRTK plugin is an immense collection of helpful tools and offers even more than the currently used tools in Maroon. The additional features can be used to improve the interaction and to increase the overall usability. For example, the `VRTK_PanelMenuController` (VRTK, 2019b) allows displaying menu items as a panel which can be controlled via the controller. It could be used as a toolbox for helpful gadgets (e.g. a calculator) in the VR experiments. Controller tooltips (VRTK, 2019a) could provide information about the objects and their interactions. The radial menu (VRTK, 2019c) could give an extra level of interaction and could be used for additional controls in future experiments.

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[1] https://www.khronos.org/openxr

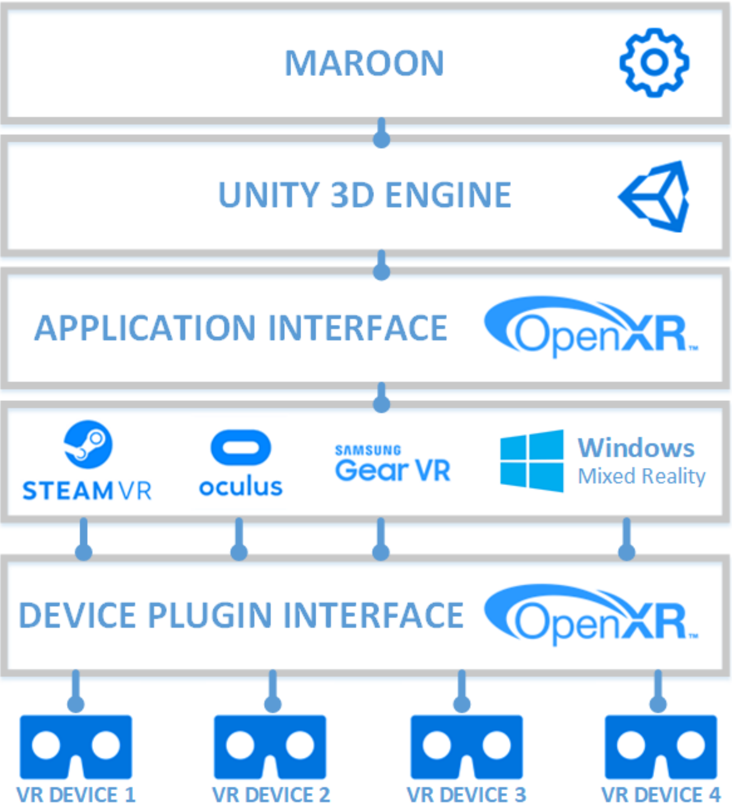

Figure 8.1.: OpenXR - Solving XR fragmentation

9. Summary and Outlook

Topics from the fields of natural sciences, technology, engineering, and mathematics are significant drivers of innovation and will become more and more relevant in the future. But teaching and learning these disciplines are still a challenge. Students find these subjects uninteresting and do not understand why they have to learn them. The goal is to motivate students to learn, but also to understand the concepts. Active learning has proven to be a valuable method to involve students directly in the learning process. Interactive simulations, visualizations, virtual or remote laboratories, as well as gamified learning environments are powerful tools to support teaching and enhance engagement, immersion, and motivation. Virtual environments are becoming increasingly important in this context. Virtual reality technologies enable an immersive way to explore the dimensions of virtual worlds and allow users to interact directly with the environment which opens great potential to develop motivating and engaging learning experiences.

In this theses, we presented the design and conceptual model of the immersive physics laboratory Maroon with a focus on the following new experiments:

- Falling Coil
- Faraday's Law
- Capacitor
- Huygens Principle

Maroon was designed as an interactive, extensible virtual laboratory environment that allows learning physical phenomena in an immersive, engaging and motivating way. The laboratory acts as a three-dimensional menu where the users can choose an experiment by entering the learning station. The laboratory was realized as a classic desktop application and as a virtual reality application compatible with the HTC Vive. For this purpose, we developed specific user interfaces which allow users to interact with the laboratory environment. The developed experiments implement the different user interfaces and allow users to change various parameters of the experiments to observe the impact on the experiment. Through field visualizations and wave representations, invisible phenomena become visible and enable a better understanding of the underlying physical concepts.

The evaluation of the laboratory environment showed that Maroon as an interactive, immersive experiment has a high potential for improving physical learning. Users described both laboratory variants as positive and would like to learn with the environment. In comparison to the classical computer-based version, the VR experience was received as more engaging and immersive. The users mentioned that the interactive, realistic and natural design in VR facilitates interaction and practical use. This improved also the feeling of immersion and led to higher learning outcomes. Users of the VR version were able to answer the question much better than PC users. In conclusion, Maroon is an engaging and immersive experiment environment which helps students to understand invisible phenomena by providing different visualizations. It makes learning physics more interesting and easier to understand. However, there is still potential for enhancements and improvements to make the system ready for practice.

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Appendix

Appendix A.

DVD Contents

The attached DVD contains the practical and the theoretical part.

A.1. Practical Part

- Unity 2018.4 LTS installer
- The latest version of Maroon including the experiments.
    - PC and VR Build
    - WebGL Build

A.2. Theoretical Part

- PDF version of this thesis
- Evaluation questionnaires
- Summary of the evaluation results

Appendix B.

Installation Guide

B.1. System Requirements for running Maroon

- Desktop:
  - Microsoft Windows 7 SP1+
  - Graphics card with DX10 (shader model 4.0) capabilities
  - CPU: SSE2 instruction set support
- WebGL: Any recent desktop version of Firefox, Chrome or Edge.

B.2. Installation

- Copy the build folder (PC, VR, or WebGL) to a local drive on the PC.
- PC/VR: Start “Maroon.exe”.
- WebGL: Open “index.html” in a web browser.

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