11th International Conference of the Immersive Learning Research Network
Selected Academic papers for the iLRN Proceedings

DOI: https://doi.org/10.56198/bjn3n897

# Extended Abstract—An Adaptive Virtual Lab Environment for Educator-Driven Web Integration

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**Abstract.** Teaching science, technology, engineering, and mathematics (STEM), particularly physics, faces challenges in engaging students and developing problem-solving skills. Traditional methods often fail to address these issues. Interactive learning environments, such as virtual laboratories, offer promising alternatives. This paper presents a virtual laboratory environment integrated into web applications, to support teaching of complex concepts like differential equations, 3D vectors, and optics. The modular structure allows seamless integration into different course websites, enabling educators to customize simulations for various learning scenarios. The virtual lab provides students with interactive simulations that facilitate exploration, experimentation, and visualization, enhancing the understanding of challenging physical phenomena. By manipulating parameters and observing dynamic changes, students gain hands-on experience in a safe, engaging environment.

**Keywords:** Virtual Laboratory, Interactive Learning, STEM Education.

## 1 Introduction

Science, technology, engineering, and mathematics (STEM) education is often challenging and time-consuming. It is a driving factor for innovation as well as economic growth and has major significance for the occupational sector [1, 2]. A major issue here is the lack of graduates in these fields. Many students find STEM areas boring, challenging, and complex [3]. In physics, the application of differential equations is pervasive and foundational, forming an indispensable tool for modeling and understanding a broad range of physical phenomena. These equations serve as a bridge between theoretical principles and real-world observations, enabling physicists to formulate precise descriptions of dynamic systems. The ability to solve problems independently is a key element here. Without this competence, students often lack the understanding of how to combine their knowledge with real-world examples [4].

Teaching problem-solving using traditional teaching approaches is often challenging and not very effective. Interactive learning approaches and interesting exercises can help students acquire these skills. Active learning is characterized by interactive and engaging classes comprising group work and a student-focused approach [5, 6]. Constructivist learning suggests that learners actively construct their own understanding by connecting new information with their existing knowledge base. This approach encourages deeper cognitive engagement, as students are not passive recipients of information but active participants in the learning process [7]. Similarly, inquiry-based learning emphasizes the importance of students taking an active role in their education through exploring, questioning, and investigating real-world problems [8, 9]. With the usage of simulations, technical real-world models, or hypothetical systems, experiments can still be conducted with a high amount of realism and safety. Students are encouraged to interact with the phenomena, transforming the visual into a hands-on experience [10]. D'Angelo et al. [11] consulted 59 studies on simulations in education and found an overall beneficial effect. Thisgaard and Makransky [12] confirmed these findings by concluding, that simulations are at least as efficient as traditional teaching methods.

A great way to include this in normal classrooms is the use of virtual laboratories. These often combine several simulations of one or more subjects, making them easily accessible for students and teachers. The high accessibility makes virtual laboratories more collaborative and remotely accessible than their real-world counterparts. Another benefit is flexibility, allowing learners to swiftly gain access to several aspects of a discussed topic. However, the greatest merit is the high amount of freedom, meaning that virtual laboratories are not bound to the same principles as real experiments, resulting in possibilities exceeding real-world setups [13, 14]. Corter et al. [15] observed that their usage is at least as efficient in teaching as in real laboratories.

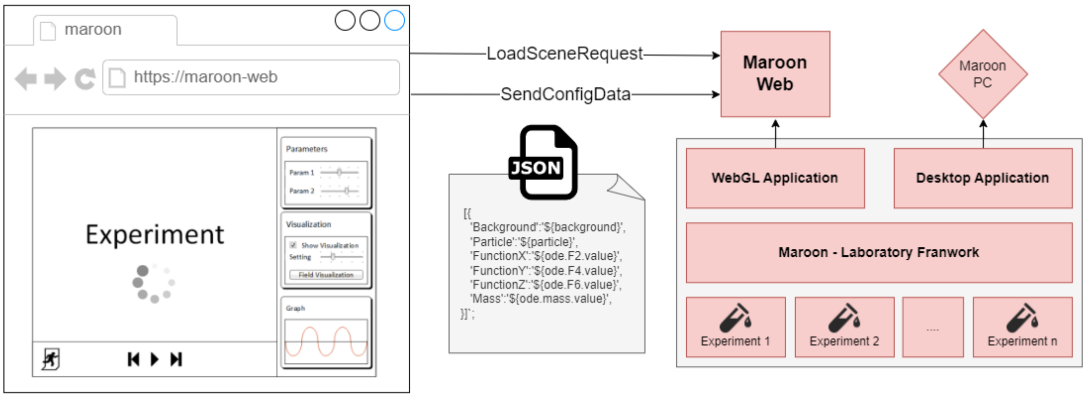
In this paper, we present a virtual physics laboratory environment for web applications to allow educators an adaptive integration into their course websites. We implemented three different simulations and visualizations to support the understanding of difficult concepts such as differential equations, partial differential equations, vectors in 3D, gradient, and divergence in a web application. The modular design allows individualized integration into customized websites and gives the flexibility to extend it with different learning scenarios.

## 2 Virtual Lab Environment

To engage students in physics, we developed a virtual laboratory environment for web applications, Maroon Web. The environment offers a 3D lab experience with a variety of interactive and engaging learning approaches that make learning more enjoyable. Users can explore various simulations and experiments by navigating around a laboratory hub in a first-person perspective. After selecting an experiment, the user is sent to a different scene where the user can manipulate the experiment's behavior by changing specific parameters. Users can run integrated simulations and learning activities at any time and as often as they like to support exploration without suffering any consequences of the mistakes they make. These simulations actively encourage engagement by providing dynamic visualizations, enabling students to adjust variables and witness the immediate impact of their decisions. This hands-on interaction supports constructivist learning, where students build new understanding by linking novel experiences with prior knowledge. The open-ended nature of the experiments fosters inquiry-based learning. Students can formulate hypotheses, test different scenarios, and draw conclusions based on their observations, fostering critical thinking.

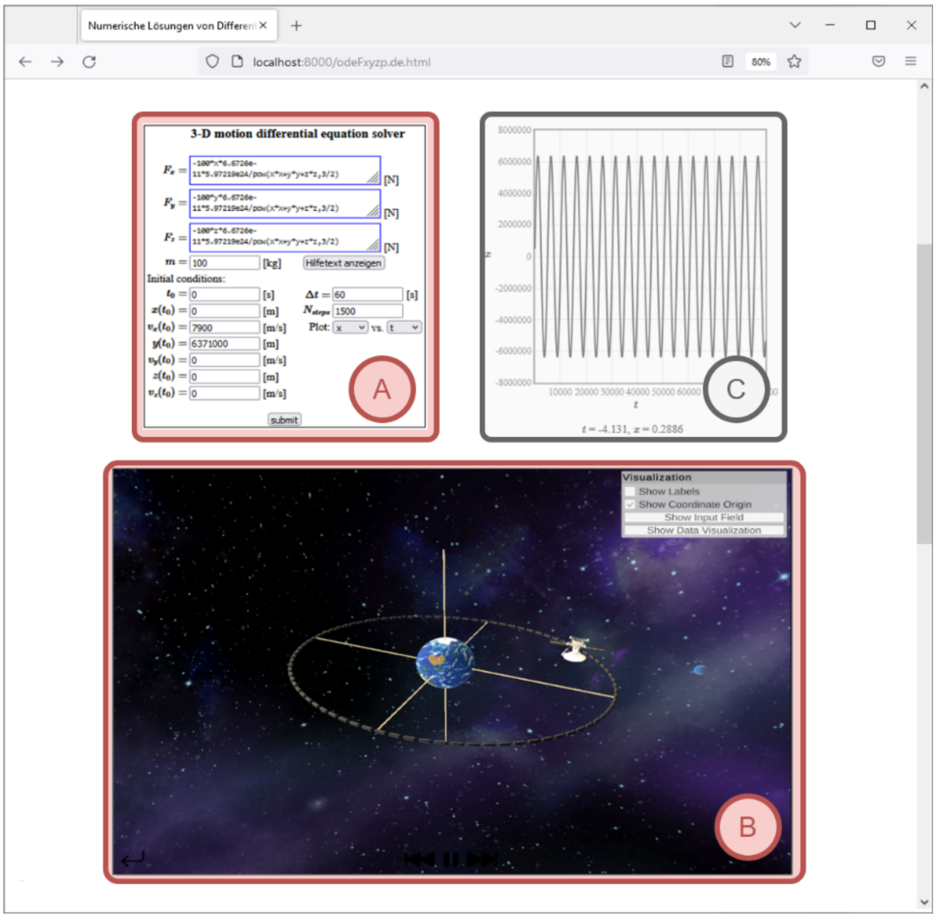
### 2.1 Web Architecture

The laboratory framework was developed in Unity and can be extended in a modular way so that different learning scenarios can be easily added. While the Unity physics engine handles acceleration, collision, gravity, and forces, Maroon extends the physics engine and builds a new layer on top of the engine. The experiments are based on this layer and provide physical modifications and visualizations. Fig. 1 shows the web architecture and the communication between the Maroon application. Teachers can integrate the web version of the experiment into custom websites and start the experiment with their own defined parameters via a submit button. The WebGL Receiver class provides an *OnIncomingData* event, which makes it possible to handle parameters received from an external JavaScript function. The callback function triggers the calculation and visualization process of the logical layer. The transmitted JSON data contains parameter values. It allows users to customize the simulation background and object appearance. Fig. 2 illustrates the connection between a 3D motion differential equation solver (A) and the Maroon web build (B). The web build is loaded into a div-container, which allows a modular structure that can be easily embedded into different web environments. This modular design increases the ability to integrate the experiment seamlessly into other educational web platforms. The possibility of integrating optional web content (C) offers teachers the opportunity to display additional information about the experiment and make the lesson even more attractive for the students.



```
[{
  'Background':'${background}',
  'Particle':'${particle}',
  'FunctionX':'${ode.F2.value}',
  'FunctionY':'${ode.F4.value}',
  'FunctionZ':'${ode.F6.value}',
  'Mass':'${ode.mass.value}',
}]`;
```

**Fig. 1.** Maroon Laboratory Web Architecture.



3-D motion differential equation solver

$F_x$ = -100*x*6.6726e-11*5.97219e24/pow(x*x+y*y+z*z,3/2) [N]

$F_y$ = -100*y*6.6726e-11*5.97219e24/pow(x*x+y*y+z*z,3/2) [N]

$F_z$ = -100*z*6.6726e-11*5.97219e24/pow(x*x+y*y+z*z,3/2) [N]

$m$ = 100 [kg]

Initial conditions:

$t_0$ = 0 [s]
$x(t_0)$ = 0 [m]
$v_x(t_0)$ = 7900 [m/s]
$y(t_0)$ = 6371000 [m]
$v_y(t_0)$ = 0 [m/s]
$z(t_0)$ = 0 [m]
$v_z(t_0)$ = 0 [m/s]
$\Delta t$ = 60 [s]
$N_{steps}$ 1500
Plot: x vs. t

$t = -4.131$, $x = 0.2886$

☐ Show Labels
☑ Show Coordinate Origin

**Fig. 2.** Web Integration: (A) 3D motion differential equation solver providing data to the laboratory web build, (B) Web build loaded into a div-container, (C) Optional web content to display additional information.

## 2.2 Experiment Setup

This section will introduce the conceptual design of the experiments and simulations implemented in Maroon Web. The goal is to simulate and illustrate different physical phenomena by providing various virtual experiments. Each experiment scene implements the general experiment and extends it with the respective user interface. The experiment is fully functional on its own and contains all physical relevant components, including visualization elements. All simulations are based on the Physics M[1] course at Graz University of Technology. The following subsections describe the different experiments that have been realized in the web application.

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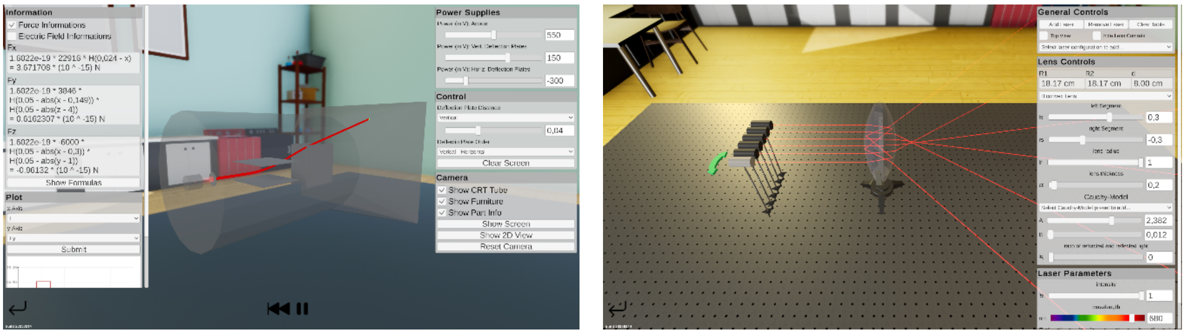
[1] https://lampz.tugraz.at/~hadley/physikm

**Three-Dimensional Motion Simulation.** The three-dimensional motion simulation is primarily meant to illustrate how motion can be described by differential equations. The simulation shows the concept of motion, power, work, and kinetic energy in three dimensions. The user can choose settings from predefined simulations via a dropdown menu or set their parameters. The parameter fields allow setting the forces in $x$, $y$, and $z$ direction and the mass of the object. The initial conditions describe the values at time $t_0$ like the time steps between calculation points, the calculation steps, $x$, $y$, and $z$ position and their velocities in each direction. In the initial phase, the forces are parsed to replace the variables in the equation with dynamic values. Using the implemented 3D-motion differential equation solver, the parsed equation with the initial condition is then solved step by step via a 4th-order Runge-Kutta method [16]. Via the included data visualization graph, the user can display certain calculated values over time like the position, velocity, and forces of an object moving, the change in kinetic energy, the work done, and the power. With the help of these tools, students should learn to calculate the trajectory of an object given the forces and its initial conditions.

**Cathode Ray Tube Simulation.** Based on the same underlying motion equation, the cathode ray tube (CRT) experiment illustrates the electric deflection of an electron beam in which the electrons are accelerated through a voltage $V_x$ towards a positively charged plate. Some of the electrons pass through a small hole in the plate creating an electron beam directed towards a region where an electric field is established by applying a voltage $V_y$ between two metal plates separated by a distance $d$. Fig. 3a shows an example setup of the experiment. The users are presented with the virtual model of a basic cathode ray tube featuring an electron gun, two sets of deflection plates for horizontal and vertical deflection as well as a phosphorescent screen. The main part of the visual representation is the red electron beam. It gives a physically accurate representation of an electron's path through the CRT. The user interface is split into two functionalities, control on the right side and information on the left side of the screen. The users can change the parameters of the experiment via the control panels. The voltage can be controlled to influence the deflection of the electron beam. Furthermore, the setup can be changed by controlling the plate distance and switching between different plate layouts. The last control panel can be used to switch between different camera angles and toggle the visibility of the furniture or the glass tube. When interacting with the experiment options, the user gets immediate visual feedback via the simulated model. The panels on the left side of the screen display further information regarding the chosen parameters. They show the formulas and calculated results for the electric fields as well as the forces acting on an electron in all three directions. Furthermore, a plot panel can be used to display additional information regarding the spatial or temporal change in location, velocity, or force.

**Light Ray Reflection and Refraction Simulation.** For solving the optics experiment, users have to handle vector algebra. When a ray traveling in direction $\vec{r}$ strikes a surface with normal $\hat{n}$, the direction of the reflected wave can be calculated by decomposing $\vec{r}$ into a component normal to the plane and a component parallel to the plane, $\vec{r} = \vec{r}_{\|} + \vec{r}_{\perp}$. The component normal to the plane is $\vec{r}_{\perp} = \vec{r} \cdot \hat{n}\hat{n}$ and the component parallel to the plane is $\vec{r}_{\|} = \vec{r} - \vec{r}_{\perp}$. Upon reflection, the normal component of the ray is inverted so the reflected ray travels in the direction $\vec{r}^{\,\prime} = \vec{r}_{\|} - \vec{r}_{\perp}$. The lens model in the web build consists of two spherical surfaces and one cylindrical surface. Depending on the user input, the lens can be concave or convex on either side. An intersection of a ray and a lens is calculated by calculating intersections of the line that the ray follows and the spherical surfaces as well as the intersection of the line and the cylindrical surface. If more intersections of the line and the surfaces occur, the first point the ray strikes is taken and the surface normal is calculated at this point. Reflected and/or refracted ray directions are then calculated based on ray wavelength, angle, and material properties. With those directions and the intersecting point, new rays are constructed, and the calculation is repeated recursively. The segment between a ray's starting point and its intersection is then saved for rendering. The environment resembles a stylized optics table with a central lens assembly and light sources, which visualize the origins of the simulated rays. The control panel also allows the user to add an entire, predefined row of light sources with predefined wavelengths to quickly set up an experiment arrangement. These arrangements currently include a parallel row of red laser pointers, three rows of parallel red, green, and blue laser pointers to simulate chromatic aberration, a focused laser array to mimic point light sources as well as a shifted, focused laser array. Three buttons enable the user to add a single laser pointer, remove a selected laser pointer, and clear the entire table.



```
Fx
1.6022e-19 * 22916 * H(0,024 - x)
= 3.671708 * (10 ^ -15) N
Fy
1.6022e-19 * 3846 *
H(0.05 - abs(x - 0,149)) *
H(0.05 - abs(z - 4))
= 0.6162307 * (10 ^ -15) N
Fz
1.6022e-19 * -6000 *
H(0.05 - abs(x - 0,3)) *
H(0.05 - abs(y - 1))
= -0.96132 * (10 ^ -15) N
```

Power Supplies: 550; 150; -300

Deflection Plate Distance: 0,04

R1 18.17 cm, R2 18.17 cm, d 8.00 cm

ls 0,3; rs -0,3; lr 1; dt 0,2; A 2,382; B 0,012; 0; intensity 1; wavelength 580

(a) Cathode Ray Tube (b) Light Ray Reflection and Refraction

**Fig. 3.** Web Physics Experiments.

## 3 Conclusion and Outlook

In conclusion, the development of virtual experiments for physics concepts like differential equations and vectors in 3D using the Maroon web architecture represents a powerful tool for enhancing interactive and engaging learning experiences for web applications. The modular design not only allows individualized integration into user-defined websites, it also gives users the flexibility to expand the range of learning scenarios. The presented use cases demonstrate different ways in which students can manipulate parameters, observe dynamic changes, and gain practical experience in fields such as mechanics, electromagnetism, and optics.

The graphical representation of experiments aids in better comprehension and retention of complex physics concepts. Integrating 3D models and interactive elements enhances the overall appeal of the virtual laboratory, making physics learning more enjoyable for students. In previous studies, we have already evaluated different immersive and engaging lab variants from the students' and teachers' perspectives. We have demonstrated the potential of immersive learning techniques in the field of STEM and discussed the advantages and disadvantages [17]. The presented Maroon web architecture adds the ability to define experiment parameters and settings via external web content to the lab environment, increasing the platform's adaptability for different educational contexts. By combining technological innovation with pedagogical depth, the platform offers a dynamic and immersive environment where students can explore, experiment, and engage and deepen their understanding of physics.

Technical constraints, such as browser performance and WebGL compatibility, may affect the scalability and accessibility of certain experiments. Additionally, while the modular design allows for customization, integrating highly specialized simulations or expanding to other STEM fields may require further development efforts. To address these challenges and ensure the effectiveness of the platform, future work will focus on implementing structured assessment frameworks and data-driven evaluation metrics. By integrating tools to track student progress, interaction patterns, and conceptual understanding, we aim to gain deeper insights into learning outcomes and refine the learning experience accordingly.

## References

1. Xie, Y., Fang, M., Shauman, K.: STEM Education. Annual Review of Sociology. 41, 331–357 (2015). https://doi.org/10.1146/annurev-soc-071312-145659
2. Rothwell, J.: The hidden STEM economy. Metropolitan Policy Program at Brookings Washington, DC (2013).
3. Olson, S., Riordan, D.G.: Engage to excel: producing one million additional college graduates with degrees in science, technology, engineering, and mathematics. Report to the president. Executive Office of the President. (2012).
4. Buffler, A., Allie, S.: Towards an active learning environment in physics: developing problem solving skills through cooperative learning. In: Proceedings of the Annual Conference of the South African Association of Academic Development. pp. 15–29 (1993).
5. Devlin, T.J., Feldhaus, C.R., Bentrem, K.M.: The Evolving Classroom: A Study of Traditional and Technology-Based Instruction in a STEM Classroom. Journal of Technology Education. 25, 34–54 (2013).
6. Pirker, J., Riffnaller-Schiefer, M., Gütl, C.: Motivational active learning: engaging university students in computer science education. In: Proceedings of the 2014 conference on Innovation & technology in computer science education. pp. 297–302 (2014).

7. Fernando, S.Y.J.N., Marikar, F.M.M.T.: Constructivist Teaching/Learning Theory and Participatory Teaching Methods. Journal of Curriculum and Teaching. 6, 110–122 (2017).
8. Bogador, C.J., Camarao, M.K.G., Matunding, C.G., Sombria, K.J.F.: Challenges and Benefits of Inquiry-Based Learning in Physics. 1. 5, 2716–2732 (2024). https://doi.org/10.11594/ijmaber.05.07.26
9. Jerrim, J., Oliver, M., Sims, S.: The relationship between inquiry-based teaching and students' achievement. New evidence from a longitudinal PISA study in England. Learning and Instruction. 80, 101310 (2022). https://doi.org/10.1016/j.learninstruc.2020.101310
10. Lunce, L.M.: Simulations: Bringing the benefits of situated learning to the traditional classroom. Journal of Applied Educational Technology. 3, 37–45 (2006).
11. D'Angelo, C., Rutstein, D., Harris, C., Bernard, R., Borokhovski, E., Haertel, G.: Simulations for STEM learning: Systematic review and meta-analysis. Menlo Park: SRI International. (2014).
12. Thisgaard, M., Makransky, G.: Virtual Learning Simulations in High School: Effects on Cognitive and Non-cognitive Outcomes and Implications on the Development of STEM Academic and Career Choice. Frontiers in Psychology. 8, (2017). https://doi.org/10.3389/fpsyg.2017.00805
13. Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V.M., Jovanović, K.: Virtual laboratories for education in science, technology, and engineering: A review. Computers & Education. 95, 309–327 (2016). https://doi.org/https://doi.org/10.1016/j.compedu.2016.02.002
14. De Jong, T., Linn, M.C., Zacharia, Z.C.: Physical and virtual laboratories in science and engineering education. Science. 340, 305–308 (2013).
15. Corter, J.E., Nickerson, J.V., Esche, S.K., Chassapis, C., Im, S., Ma, J.: Constructing Reality: A Study of Remote, Hands-on, and Simulated Laboratories. ACM Trans. Comput.-Hum. Interact. 14, 7–es (2007). https://doi.org/10.1145/1275511.1275513
16. Hairer, E., Lubich, C., Roche, M.: The numerical solution of differential-algebraic systems by Runge-Kutta methods. Springer (2006).
17. Holly, M., Pirker, J., Resch, S., Brettschuh, S., Gütl, C.: Designing VR experiences–expectations for teaching and learning in VR. Educational Technology & Society. 24, 107–119 (2021).