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PhysLab – A 3D Virtual Physics Laboratory of Simulated Experiments for Advanced Physics Learning.

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Abstract

We introduce a virtual physics laboratory, "PhysLab", created using 3D video game technology suitable for advanced level physics courses in secondary schools. This comprises 32 simulated experiments covering a range of physics topics, selected in collaboration with practicing school teachers. PhysLab is made available at no cost for the physics education community as an installable application, ready to run, while giving the instructor some control over how information is displayed, and suitable ranges of experimental parameters. While we focus on the theory, design and pedagogical aspects of PhysLab, we provide some critical reflections on the use of simulations in physics teaching in general, and especially how these could be most effectively used in the physics classroom. The experiments are classified according to their nature: supporting theory; "What if"-scenarios, like playing badminton on the Moon; or as hypothetical situations, such as what happens if you drop your home town into a hole through the centre of the Earth. It is not our intention to advocate the replacement of real practical work; we suggest various ways in which simulations can be integrated into the classroom, including instruction and real practical work. We also discuss the details of several PhysLab simulations: the Wilberforce Pendulum; oscillations of a mass on a rubber band, which involves non-linearity; the Drude theory of electrical conduction; the Cyclotron, and a "Journey to the Centre of the Earth".

Introduction

We present a virtual physics laboratory, "PhysLab" comprising 32 interactive experiments designed to support advanced-level physics courses. PhysLab is suitable for all modes of learning and teaching. It can be used by teachers during development of concepts and theory; they may use it to provide closely-guided experiments to help students investigate and understand those concepts. We suggest its main strength is to facilitate student investigations, in the form of guided-inquiry, where students are able to select and manipulate experimental parameters, collect data and investigate ideas. Unlike other simulations, such as the ubiquitous PhET simulations developed at the University of Colorado, Boulder [1], PhysLab contains visually realistic experimental apparatus that can be found in a typical school laboratory setting. We argue that this aspect is crucial, since it allows students to make *direct observations* of experimental phenomena before collecting and analysing data. We offer PhysLab to the physics education community, with the hope that interested teachers will come together to form a community of practice, researching the use of simulations in physics learning and teaching.

A screenshot of a typical experiment, the oscillations of a mass connected to a rubber band, is shown in Figure 1. On the left is the apparatus, on the right is a real-time graph of the displacement of the mass; clearly there is non-linearity at play here. Parameters of the system can be changed by right-clicking on the apparatus; variables displayed on the real-time graph can be chosen by right-clicking on the graph.

We do not suggest that simulated experiments should replace classroom practicals which develop skills not possible to learn outside of the real laboratory. Several suggestions of how to integrate simulations with classroom practicals and also instructor exposition of theory are discussed in the section below.

Theory and Design of PhysLab

The starting point for the design and development of PhysLab was a focus group of 5 teachers of A-Level physics in the UK. Central to discussions was the choice of experiments; teachers proposed experiments that would support the teaching of concepts they found challenging, and also where they felt experimentation was necessary, but the required apparatus was not readily available.

The Experiments

Table 1 lists the 32 PhysLab Experiments; we propose four classes of experiments, (the column “Classes”). First are those intended to relate directly to teaching concepts or *theory*, e.g. to test the theory of collisions in one dimension, the motion of particles in electric or magnetic fields, or the Drude theory of conduction. Second are *What-if?* experiments, which take classical scenarios, such as projectile motion, but extend this to an unfamiliar setting such as asking “What is it like to play badminton at the top of Mount Everest, or on the Moon? Third are *scaling* experiments that visualise physical processes operating at extremes of scales of length or time, such as atomic orbits and gravitational orbits, the launch of a Saturn-V rocket, or the Drude model of electrical conduction. The final class is *hypothetical* experiments that cannot realistically be performed, but which could be used to creatively explore (and challenge) physics theory. Examples could include the motion of your town or city when dropped into a hole through the centre of the Earth, motion of objects with negative mass, and oscillations in a cylinder divided into positive and negative gravity.

Experiments have been chosen to work together in the context of teaching a topic. These are shown in Table 1, column “Relationships”. Consider for example PhysLab’s oscillation group. First are experiments that *introduce* some theory or concepts, e.g. the mass on the spring, or the pendulum. These two are connected by the relationship *compare*; changing the mass of the former changes the oscillation period, but not for the latter. The relationship *enhance,* serves to deepen a model, e.g., the mass oscillating on a rubber band (which has a non-linear force-extension relationship) *enhances* the concept of simple harmonic motion. The relationship *reduce* simplifies some aspect of a model, e.g., moving from a mass on a spring to a mass tethered on an air-track removes the effects of gravity. Introducing the Wilberforce pendulum *extends* the mass on a spring model with an additional physics dimension (the rotation of the bob). The relationship of *apply* takes a ‘laboratory’ situation and applies it to a real-world application, e.g., understanding the behaviour of a mass on a spring can be applied to an automobile suspension; the rubber band model can be applied to a mountain bike suspension. The final relationship we refer to as *transcend* where theory of oscillations is applied to hypothetical experiments, such as oscillations in a gravity tube, or falling through the centre of the Earth.

Pedagogy and Classroom Use

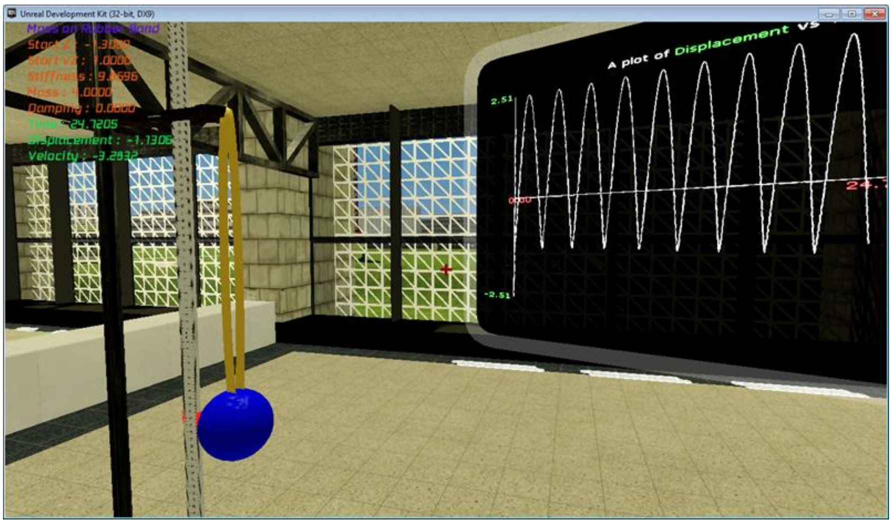
As already mentioned, there are three dimensions of ‘doing science’; theory, experiment and simulation [2], where simulation is included to reflect the activities of professional scientists. Within the classroom, we suggest that simulations can support teachers’ *expository* activities presenting concepts and theory; they can also complement laboratory *experimentation*; they can also be used in student *autonomous* activities, e.g. homework. These types of are shown in Table 1 column “Classroom Use”. Experiments labelled “L” can be linked to real classroom practicals, e.g., by allowing students to get to know a scenario through the simulation, and then performing the real experiment. Prior research sees the strength of simulations in inquiry-based investigations [3], and there is even the suggestion that they can help in authentic student research [4]. While we feel this suggestion is perhaps too strong, our own experience of *extended investigative work* (teaching Nuffield A-Level Physics in the 1980’s) suggests that such work provides a cradle where theory and experiment are both linked and tested together, where students effectively test their mental models of physics concepts. The contemporary physics classroom has little time for such extended work, simulations fit ideally into this role. Working with simulations, students take on ownership of investigations, where they are able to manipulate both variables and ideas. However, we firmly believe that simulations should not replace real classroom experiments. It is also important for teachers to have confidence that simulations correctly agree with reality. As explained below, this has been established for all PhysLab simulations.

Research shows that guidance is crucial for inquiry-based learning [5], and that the teacher-centred use of simulations is the most effective way of using simulations [6]. We agree that the role of the teacher is crucial, as opposed to scaffolding provided within the simulation, but argue for a more varied role of the teacher, drawing on our own teaching experience. When a new topic or concept is introduced, before any discussion of theory takes place, students should enter PhysLab and conduct a short guided qualitative investigation focusing on *direct observations*. This will start the formation of students' mental models and ground the following teacher presentation of the theory. Then, students will enter PhysLab and conduct specific guided experiments to test (and develop understanding of) the presented theory. Finally, at the end of the topic, students should be allowed to enter PhysLab to conduct discovery-based investigations with no or minimal guidance. This approach will foster both the learning of physics concepts, and also how to work as a physicist.

The Architecture of PhysLab

The architecture of PhysLab draws upon the *computation-visualisation-interaction* model we have developed for our undergraduate classes over the last 10 years. The *computation* system refers to the code that underlies the simulation. This involves solving systems of ordinary differential equations (that capture the dynamics of the physical system, often non-linear). We do not expect students to engage in computer programming unlike some physics simulations [2]. However, it is extremely important for users of any simulations to have confidence in their 'correctness'. This means two things. First, simulation computer code must faithfully express the underlying mathematical models of the physics, e.g., our rubber-band oscillator code correctly simulates a given model of a non-linear rubber band. This check is called *verification* which we achieve through a comparison of data produced by the PhysLab computational engine with equivalent data produced by the gold-standard software MATLAB[1]. Second, data generated by the simulation must agree with real-world experimental data; this is called *validation*. An example is PhysLab's badminton simulation, where we compare simulation data with experimental results reported [7]. Where experimental data is not available, we *validate* against theory; the argument here is that theory has been developed in association with experiment.

Concerning the *visualisation* component, we propose two poles of choice, either *realistic* or *symbolic*. There is also the design decision to visualize in 2D or 3D. Prior research on simulation visualisation has focused on the effect of visualisation on student learning. It is suggested that no extraneous detail should be present, and that cause-and-effect relations should be made clear in the visualization [6]. There is the suggestion that realistic visualisation may not enhance student learning, and indeed may hamper it [6]. The PhET movement has chosen to employ *2D symbolic* representations, thus avoiding extraneous detail, yet there are reports of students finding multiple representations challenging [8]. We challenge this; our 3D realistic simulations, created using a 3D video game engine have shown no signs of impairing student learning in our trials; students report being highly-motivated, many indicating their experience is familiar, similar to video games. We argue that it is precisely due to the realism of our experiments that students do not experience extraneous detail, and do not have to deal with the cognitive load of interpreting symbolic representations of apparatus.



Mass on Rubber Band
Start z : -1.3000
Start vz : 1.0000
Stiffness : 9.8696
Mass : 4.0000
Damping : 0.0000
Time : 24.7205
Displacement : -1.1306
Velocity : -3.2832

Figure 1. Oscillations of mass on a rubber band, with real-time graph, showing non-harmonic oscillations.

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[1] https://www.mathworks.com/products/matlab.html

	Experiments	**Classes**	**Classroom Use**	**Relationships**
	Oscillation Group			
1	Mass on a Spring		E,L	*introduce, compare* (6)
2	Mass on a Rubber Band		I,L	*enhance* (1)
3	Mass with springs on air-track		E,L	*reduce* (1)
4	2D horizontal oscillation of mass on 4 springs		I	*extend* (3)
5	Normal Modes, 2 masses tethered with 3 springs		I	*extend* (3)
6	Simple Pendulum		E,L	*introduce, compare* (1)
7	Wilberforce Pendulum		L,I	*extend* (1)
8	Gravity Tube	H	I	*transcend*
9	Journey to the Centre of the Earth	H	I	*transcend*
10	Mountain bike		I	*apply* (2)
11	Monster Truck suspension	W	I	*apply* (1)
12	Water molecule	S	I	*apply* (4)
	Momentum Group			
13	Air track collisions, two masses		E,L	*introduce*
14	Air track collisions, multiple masses, “cannon”		L,I	*extend* (13)
15	2D collisions		E,L,I	*extend* (13)
16	Full billiard table		I	*apply* (15)
	Electric and Magnetic Field Group			
17	Motion in a single B-field	S	E,L	*introduce*
18	Motion in 4 localised B-fields, rectangular geometry	S	L,I	*enhance* (17)
19	Cyclotron	W	I	*introduce, enhance* (17)
20	Particle deflection in E-field (electron beam tube)		E,L,I	*introduce*
21	Particle deflection in E-field (ink-jet printer)		L,I	*apply(20)*
	Newtonian Dynamics Group			
22	Projectile motion (badminton game simulation)	W	E,L,I	*introduce*
23	Saturn-V rocket launch	S,W	I	*introduce, enhance (theory)*
24	Bouncing ball		E,L	*introduce, combine* (22,13)
25	“Apocalypse” fairground ride	W	I	*reduce, apply* (22)
	Central Force Group			
26	Sun and Earth	S,H	E,I	*introduce, compare* (27,28)
27	Astronaut training centrifuge		I	*enhance* (26), *combine* (26,3)
28	Bell-crank centrifuge		I,L	*compare* (27)
	Miscellanea			
29	Ripple tank interference		E,L	*introduce*
30	Classical Atom	S,H	E,I	*introduce, compare* (31)
31	Bohr Atom	S	E,I	*introduce, compare* (30)
32	Drude conduction model	S	E,I	*introduce*

Table 1. PhysLab experiments. The third column shows their classification (in addition to *theory*), W=*What if?*, S=*scaling,* H=*hypothetical*. The fourth column refers to their classroom use E=*expository*, L=*laboratory*, I=*extended investigation*. Experiments labelled “L” should be linked to real classroom practicals. The fifth column lists their inter-relationships; *introduce, enhance, extend, reduce, compare, combine, apply.*

Selected Experiments

Wilberforce Pendulum

This experiment beautifully demonstrates coupling between translational and rotational modes of oscillation in a pendulum where the bob is fixed to the spring so that the spring can exert torsion onto the bob causing it to rotate [9]. Direct observation of the experiment shows a beating transference of motion (and energy) between the translational and rotational movement of the bob. One is captivated by the bob becoming periodically at rest, a phenomenon not associated with an undamped oscillator. The mathematics of this system can be simplified to the following canonical form of ODEs which express the translational and rotational accelerations of the bob as

$$\ddot{z} = -\omega^2 z - \frac{\epsilon}{2m}\theta$$

and

$$\ddot{\theta} = -\omega^2 \theta - \frac{\epsilon}{2I} z$$

Here, the natural oscillation frequencies ω for translational and rotational motion have been made the same by setting the spring parameters, i.e. $\omega^2 = k/m = \delta/I$. The parameter ϵ is the degree of coupling between translational and rotational modes. Coupling leads to a beating between the two modes with beat frequency

$$\omega_B = \frac{\epsilon}{2\omega\sqrt{mI}}$$

A typical experiment[2], results in the graph shown in Figure 2, showing how both z and θ vary with time. However, through *direct observation*, one is captivated by the fact that the pendulum's vertical motion becomes periodically at rest, which may not be expected by a student. This is a good example of a situation where a lot of physics learning can obtain via *direct observation* with teacher guidance (classical "demonstration").

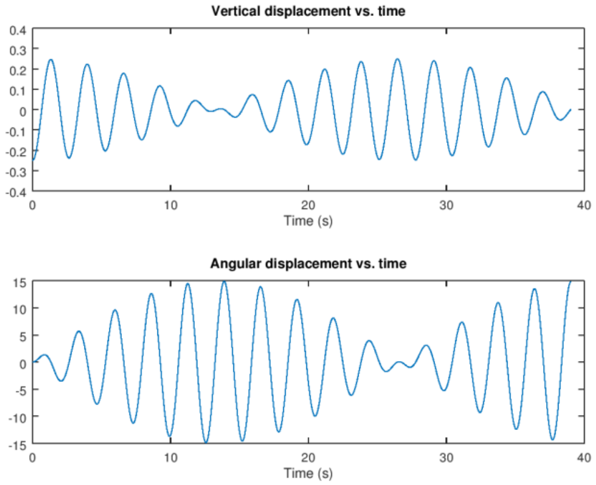

Figure 2. Vertical (top) and angular (bottom) displacements, shown versus time.

Oscillations of a Mass on a Rubber Band

This experiment is an *enhancement* of the classical mass on a spring oscillator, and leads to observations of new phenomena, and their associated concepts. When a rubber band is stretched, there are two phases of behaviour; the initial stretching unravels the entangled rubber molecules, here the force-extension relationship is

---

[2] Parameters $m = 0.495\ kg, I = 1.39 \times 10^{-4}\ kgm^2, \epsilon = 9.27 \times 10^{-3} N, k = 2.8\frac{N}{m}, \delta = 7.86 \times 10^{-4} Nm$

approximately Hookean, with force and extension proportional. When the unravelling is complete, further stretching pulls against the molecular bonds which exhibits a higher stiffness compared with the unravelling. Taking both phases together, the force-extension relationship is non-linear and so the oscillations are non-harmonic. Investigating this non-linear behaviour serves to put the sinusoidal oscillators, presented to students, into context and should re-inforce their required learning by this *enhancement* that produces a contrast. We model this non-linear force-extension relationship through the expression

$$F = -kz + \frac{B}{(z + z_0)^n}$$

The resulting force-extension curve is shown in Figure.3, together with the vertical motion of the mass[3]. The latter is clearly non-harmonic, the bob does not oscillate around the equilibrium value (0.0) and the curve is non-sinusoidal. It is clear from the graph that when the rubber band is extended the displacement undergoes a rapid reversal; this is due to a larger force as the band moves into the non-linear region.

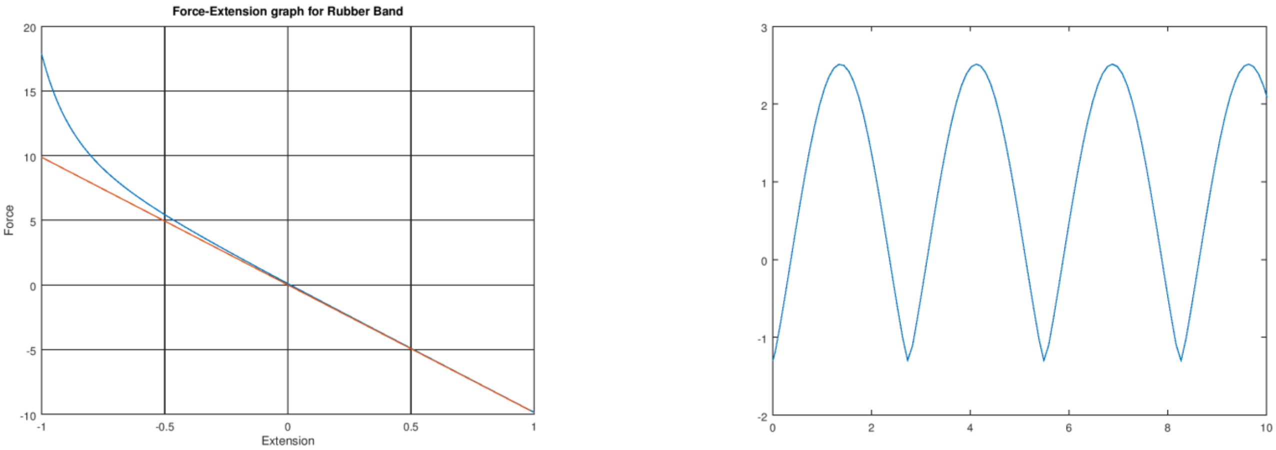

Figure 3. Left shows the nonlinear force-extension curve for a rubber band, compared with a Hookean force-extension curve, for a mass on a spring. Right shows the resultant displacement-time graph clearly showing non-harmonic oscillations.

Journey to the Centre of the Earth

This *hypothetical* experiment is remotely related to Jules Verne's 1864 sci-fi novel (and all related movies) but it does present some useful physics. Imagine dropping your place of domicile into a tunnel through the Earth, what motion would you expect? It is interesting to listen to student's answers, a useful tool for discovering their physics misconceptions. The answer to the question about the motion is simple, it's 'simple harmonic'. The force on the object of mass *m* at a distance *r* from a mass *M* is of course

$$F = -\frac{GMm}{r^2}$$

and this is surely valid where the object is located above a planet of mass *M* or on its surface. But what happens when the object descends below the planet surface. Here Gauss's law helps us out. When the object is below the surface, at a distance *r* from its centre (the radius of the planet is *R*) then it is only the mass *below* the object which gravitationally attracts. This mass is given by

$$M = M_0 \frac{4/3\,\pi r^3}{4/3\,\pi R^3} = M_0 \left(\frac{r}{R}\right)^3$$

so the force on the object becomes

$$F = -\left(m\frac{GM_0}{R^3}\right) r$$

---

[3] Parameters: *k*=9.8696 *N/m*, *m*=1kg, *B* = 0.5 *Nm*^{4}, $z_0 = 1.5m$ and *n*=4.

i.e. the force is restoring, proportional to displacement *r* with effective spring constant $\left(m\frac{GM_0}{R^3}\right)$ leading to the following expression for period

$$T = \sqrt{\frac{R^3}{GM_0}}$$

Gravity Tube

This is the second *hypothetical* experiment in the lab. Imagine two cylinders, one placed on top of the other. Gravity points downwards in the top cylinder and upwards in the lower. Clearly an object in this field will experience oscillations. Of course the oscillations are non-harmonic, and their period is amplitude dependent as can be seen from the following expression (easily deduced from kinematics)

$$T = 4\sqrt{\frac{2z_0}{g}}$$

Here z_0 is the initial displacement of the object. Investigations soon lead to the discovery that these oscillations are non-harmonic; this experiment can be used to re-inforce the concept of harmonic oscillations, and the fundamental physics behind this.

Drude Theory of Conduction

Drude modelled electrical conduction as a sea of electrons with a thermal distribution of velocities which when moving through a metal lattice collided with the metal ions [10]. Between collisions the electrons are accelerated by the electric field and so obtain a forward velocity; upon collisions this forward velocity is lost, and the electrons' velocities return to the thermal distribution. The model predicts a forward *drift velocity* which is proportional to the applied electric field. This of course yields Ohm's law. PhysLab simulates this model and provides a visualisation of the collision process; a snapshot is shown in Figure 4. Data collected by varying the applied field, and measuring the drift velocity is shown in Figure 4, where the proportional relationship is clear, as is the stochastic nature of the model. Interestingly, the fluctuations in average velocity increase with the drift velocity; this is expected since the drift velocity distribution remains roughly constant only when the drift velocity is much lower than the thermal velocity, according to the Lorentz's extension of the Drude model [11].

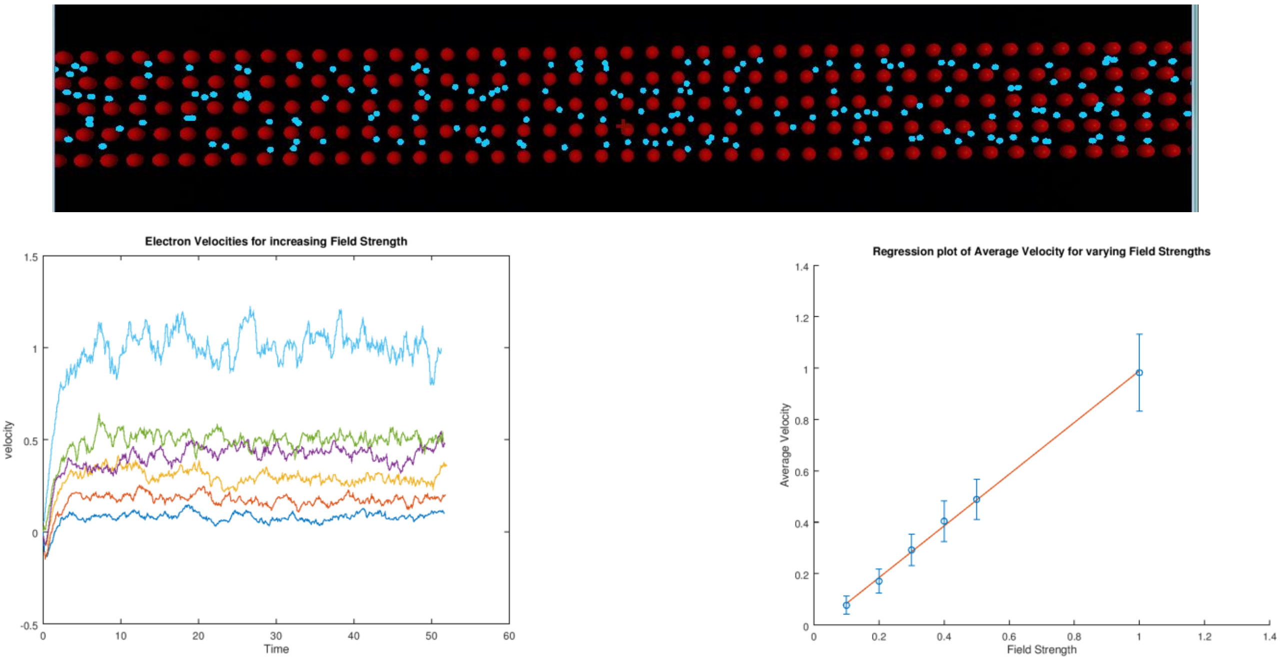

Figure 4. Top shows a snapshot of electrons (blue) moving right to left and scattering from ions (red). Bottom left shows the average velocities of all electrons for a number of applied fields. Bottom right shows the proportionality between average velocity and applied field. Bars show the standard deviations of velocities.

The Cyclotron

This experiment is a lovely (and straightforward) application of the motion of charged particles in a magnetic field, but subject to periodic acceleration by an electric field. The B-field is applied when the particle moves within two 'Ds' and serves to impart a semi-circular particle orbit with radius,

$$r = \frac{mv}{qB}$$

These orbits are clearly visible in the PhysLab simulation shown in Figure 5, together with a gap between the 'Ds' during which an E-field accelerates the particles. The above formula shows that the orbit radius is proportional to velocity. When the E-field is made to oscillate with the 'cyclotron frequency'

$$f = \frac{qB}{2\pi m}$$

then the particle experiences a series of synchronised accelerations that increases its velocity, though not linearly, since the time spent between the Ds is shorter on each orbit. The PhysLab simulation, (Figure. 5), shows this clearly where the radius of the semi-circles, (proportional to velocity) increases. Moreover, the simulation exaggerates the gap between the Ds, (neglected in text-book accounts); this introduces an additional time of flight, which then reduces the applied cyclotron frequency, clearly observed in investigations.

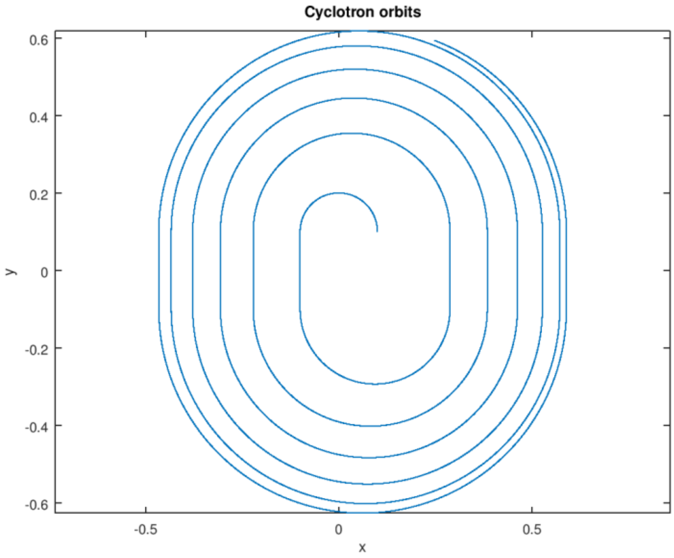

Figure 5. Plot of orbits from the cyclotron simulation. Ds edges are located at $y = \pm 0.1$.

Discussion and Conclusions

We have outlined PhysLab, a virtual physics laboratory comprising a range of simulated experiments in a 3D world, and suggest that this can be usefully deployed for Advanced Level physics courses in a range of learning and teaching activities, including extended experimentation. The design principles behind PhysLab have been presented, which we suggest could be of general interest. PhysLab does not provide any explicit instructional material or guidance prompts, since we feel this is best left to the expertise of the teacher. We offer PhysLab freely to all interested teachers, as a ready-to-run application. The corresponding author will provide guidance on installation and configuration; please contact the author directly by email. We hope to establish an active community of practice to deploy and extend PhysLab. There are of course limitations to our research and development of PhysLab. While we have focused on rigorous *verification* and *validation* of each experiment, we have not conducted extensive trials with students; this has been limited to around 50. The application runs on Windows-7 with a single-core CPU of minimum speed 2GHz. Most modern machines with built-in graphics chips will run the application; an additional graphics card may improve performance.

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