Simulations in Undergraduate Electrodynamics: Virtual Laboratory Experiments on the Wave Equation and their Deployment.

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***Abstract*—Experiments play a vital role in undergraduate engineering education: They allow students to learn the foundations of engineering in practical hands-on courses. However, lack of funding and increasing costs for equipment makes it harder and harder to supply a complete pool of experiments for large student classes. The EU funded "Library of Labs" project aims to counterbalance this development by creating a EU wide network of remotely controlled experiments and virtual laboratories. Remote experiments are here real experiments remotely controlled over a network, virtual laboratories simulation environments using the component metaphor of a real laboratories.**

In this paper, we introduce such a virtual laboratory developed at the University of Stuttgart; the aim here is to help students, here participating in the undergraduate physics course for engineers, understanding abstract phenomena by visualizing the underlying mathematics. We demonstrate this in a particular use-case, the wave equation and phenomena related to it, as they are discussed in undergraduate physics, and show how to implement this as a simulation in the virtual laboratory.

In cooperation with the physics department a deployment plan for this experiment and related experiments has been created for the lecture "Physics for Engineering" which shall also be presented and discussed.

I. Introduction

Recently, Germany's university system has been changed from the Diploma model to the two-tier Bachelor/Master program: In this study system, following the US university system, students first study a six-semester Bachelor course granting them already access to fundamental skills in their studies and early job opportunities. A successful Bachelor study is the requirement to apply for the second, extended Master studies. Due to this change, many foundational courses in the Bachelor program had to be streamlined and shortened to leave room for courses that would have been taught later in the old Diploma system. As a consequence of this streamlining, courses as fundamental as elementary experimental physics for engineers have been cut down from two to only one semester, and no time is left in these courses to provide students access to practical laboratory hands-on courses in the first semester. The first time students do have contact to real labs is delayed to the second semester where admission to the labs is granted by passing the exams in the first semester.

Unfortunately, this is a very traditional way of delivering physical content: Theoretical background is taught first, followed by practical hands-on courses allowing students to get in touch with practical aspects; the gap between theory and practical applications is here rather extreme, lots of background is simply forgotten in six month. As described in [2] this is so far unfortunate as typical students in a traditionally taught course are learning mechanically, memorizing facts and recipes for problem solving, not gaining a true understanding. Wieman and Perkins note furthermore that most people ("novices") see physics more as isolated pieces of informations handed down by some authority and unrelated to the real world [1].

In reaction to these deficiencies, Schauer introduced an alternative strategy based on integrated e-Learning, defined as "interactive strategy of teaching and learning based on the observation of the real world phenomena by the real e-experiment and e-simulations", see [2]. The procedure here is first to observe the real world phenomena, search for proper information, collect and evaluate data, then present and discuss data and results. Only then comes the explanation and the mathematical formulation of generalized laws and their consequences. The advantage of this procedure is that students have to take an active part in the teaching process. Effective tools for observing the real world are remote experiments and simulations. For studies about the effectiveness of simulations, see [1].

Building a pool of experiments sufficient to cover all of undergraduate physics is of course not an easy concern either, and a rather overwhelming task for a single university. To this end, the University of Stuttgart and ten other European institutions formed the "Library of Labs" network [3], supported by the eContent*plus* programme of the European community. The aim of this network is to setup a common infrastructure to mutually grant access to and share lab experiments and simulations available at the partners, and thus gain access to a sufficiently large pool while sharing the costs and the infrastructure.

II. On Remote Experiments and Virtual Laboratories

Within LiLa, we roughly distinguish between two types of interactive content: So called "Remote Experiments" are remotely controlled physical laboratories, hosted and maintained by one of the participating institutions. Being a scarce resource, remote experiments must be reserved and booked, and only a single student or student group can access them at a time. The University of Stuttgart does currently not provide any remote experiments, but depends on the contributions of parters, for example on the WebLab of the University of Cambridge, or the remote experiments installed at the Institute of Technology in Berlin.

"Virtual Laboratories", however, are computer simulations that follow the metaphor of a physical lab and form a framework for manifold simulations. An experiment consists here of one or many components grouped together to form a complete simulation of a physical or mathematical phenomenon. The behavior of the simulation again is measured by one or several meters, where both — the experiment and the meters — are computer algorithms. These algorithms can be either taken from a pool of already prepared experiments, or can also be modified or created by the students as required. Examples for such virtual laboratories are the "Modelica" system developed by our partner, the University of Linköping in Sweden, capable to simulate any coupled system describable by differential equations, the Easy Java Simulations (EJS) project [9], [10], or the VideoEasel system maintained and developed at the University of Stuttgart; the latter laboratory is specialized for simulating many-body particle systems, systems that are described by simple microscopic rules from which complex and often surprising macroscopic behavior emerges. A typical example for such emerging behaviour is that of "phase transitions"[4], the sudden change of a physical quantity under the change of a parameter of the system, as for example boiling of water at $100°C$. Experiments on such phenomena using virtual laboratories have been described in the past by one of the authors[5].

The common aspect of Virtual Laboratories is that, instead of only presenting a fixed, pre-programmed simulation, they reveal parts of the simulation engine and allow their users to *program* or *model* the dynamics to be simulated, and not just interact with the simulation as an electronic model of a physical experiment. Virtual Laboratories are, hence, a considerably flexible environment *for* simulations than just a specific simulation. While the underlying principle of EJS or Modelica is to describe physical processes by differential equations, VideoEasel only considers very simple time- and space discrete automata. Besides this simplicity, the large number of such simple systems coupled together generates interesting complexity and phenomena worth studying.

Even though the focus of the VideoEasel system is that of many body systems and how complex macroscopic behavior emerges from simple microscopic rules, we shall here describe a group of experiments not based on statistical mechanics, but one of the fundamental equations of physics, the wave equation. It describes spreading of all types of waves, let it be sound, water waves; phenomena like reflection and refraction are described by the same set of equations. Maxwell's equation of classical electrodynamics can be simplified to wave equations of the electric and magnetic field under certain conditions[6], and the Schrödinger equation of quantum mechanics also behaves like a wave equation with a specific diffusion relation. The latter has important consequences in physics, namely that phenomena like interference patterns known from light are also observable for rays of material particles. It is one of the fundamental experiments of quantum physics to measure this pattern which is not explainable by the model of classical particles otherwise.

These experiments, their simulation, and many other related, will be described in the section IV below.

III. Mathematical Background

In this chapter, the elementary mathematical background on the wave equation is given. Its properties discussed in this section are typically taught in undergraduate physics classes and hence need to be addressed by any type of simulation; specifically, they must be reproduced correctly to provide sufficient insight into the behaviour of waves.

The (scalar) wave equation is the following second-order hyperbolic differential equation:

$$\frac{\partial^2 \psi}{\partial t^2} = c^2 \triangle \psi \tag{1}$$

where ψ describes the *amplitude* of the field and c is the speed of the wave propagation. The wave equation describes phenomena like sound waves, electromagnetic waves or, in the approximation of small amplitudes, water waves. More important than the equation itself are, however, its properties every student of physics or engineering should be aware of, and that a suitable simulation must be able to reproduce:

- The wave equation is a linear equation; this has the important consequence that the sum of two solutions ψ_1 and ψ_2 is again a solution, i.e. $\psi_1 + \psi_2$ solves the wave equation as well. That is, the *superposition principle* holds: Waves from two sources simply add linearly without interfering each other.
- The wave equation has two noteworthy special solutions: First, *planar waves*

$$\psi(\vec{r}, t) = A \cos(\vec{k} \cdot \vec{r} - \omega t + \phi) \ ,$$

where $\vec{k}$, the so-called *wave vector*, points into the traveling direction of the wave, ϕ and A are arbitrary and $|\vec{k}|c = \omega$ holds. Second, for the special case of three dimensions, *spherical waves*

$$\psi(\vec{r}, t) = \frac{1}{|\vec{r}|} \left(A_{\text{out}}(|\vec{r}| - ct) + A_{\text{in}}(|\vec{r}| + ct) \right) \ ,$$

where A_{out} and A_{in} are arbitrary functions and describe waves outgoing from and ingoing into the origin. A spherical wave created by a harmonic oscillator at the origin would correspond to the solution $A_{\text{out}}(u) = \cos(u + \phi)$ and $A_{\text{in}} = 0$, for example. Unfortunately, a spherical wave solution of similar simplicity does not exist for two dimensions (or any even dimensional space), which is, however, the case covered by the simulation. In this case, one only has

$$\psi(\vec{r}, t) = c \int_0^{t - 1/c|\vec{r}|} \frac{cos(\omega t' + \phi)}{\sqrt{c^2 (t - t')^2 - |\vec{r}|^2}} \, dt' \ ,$$

for the initial condition of a harmonic oscillator at the origin that starts oscillating at $t = 0$. Unlike the three-dimensional case, the solution due to a short excitation at the origin does not stay on the light cone, but fills the inner of the light cone.
The important lesson is, nevertheless, that all these solutions form only different generating systems of the solutions of the wave equation, and one can, for example, generate a plane wave by a suitable linear combination of spherical waves. This is also known as *Huygens' Principle* and one of the important topics covered in undergraduate physics.

- A third important property is the conservation of energy: That is, the integral of the square of the amplitude over the whole space remains constant. The square root term in the two-dimensional solution or the $1/r$ term in the three-dimensional solution can be understood as manifestations of this principle: As a spherical wave propagates from the origin, its square amplitude must dilute proportionally to the surface of the sphere, i.e. $1/r^2$ in three or $1/r$ in two dimensions.
- The above solutions of planar and spherical waves hold only in free space; if the wave is confined by obstacles or walls, these are mathematically described by boundary conditions that need to be satisfied by the solution. While many possible boundary conditions exist, two special choices are of primary interest: First, the so-called *Dirichlet* boundary condition which requires ψ to vanish at the edge of the domain, and which describes a fixed end; and the *Neumann* boundary condition at which the spatial derivative of ψ in normal direction vanishes, also denoted as "loose end". The important properties are here that upon reflection on a fixed end, a wave is reflected back with its amplitude reversed, whereas on reflection on a loose end the wave traverses back without a phase change. A simulation of the wave equation should also reproduce these effects correctly.
- Waves interfere, creating interference patterns or standing waves; a wave reflected by an obstacle and reflected back will, for example, interfere itself and will create nodes and anti-nodes in the medium at fixed (non-time-depending) positions. This effect is called "standing waves". A simulation should also be able to demonstrate this effect.
- Waves are diffracted at obstacles. Quite unlike classical particles, waves can partially travel around obstacles, and only obstacles larger than the wavelength can severely impact the propagation of waves. One particularly important experiment on diffraction is the double-slit experiment, creating a very typical interference pattern. The very same interference pattern is, surprisingly, also visible for particles, showing that particles also have a wave nature. This is one of the very fundamental principles of quantum mechanics.

A. A Discretization of the Wave Equation

The VideoEasel system introduced above is only capable of simulating discrete systems, i.e. systems that are discrete in time, space and states; continuous differential equations are out of question. While software exist capable of solving such equations, for example in the form of the "Modelica" toolkit provided by the University of Linköping, their complexity is beyond the all-purpose approach of the virtual lab designed in Stuttgart. Hence, the goal is a suitable discretization of the wave equation (1) that is able to reproduce the phenomena described above, and is hence both didactically suitable and mathematically correct.

At first sight, a suitable approach would be the straightforward discretization of the wave equation by a discrete Laplacian and a discrete time derivative, hence replacing it by a scalar second order difference equation. However, it turns out that this approach is not particularly useful, especially energy conservation is considerably hard to ensure in this approach. A considerably more interesting and fruitful approach is that of proposed by H.J. Hrgovčić[7] in his thesis: Similar to the Dirac equation replacing a scalar differential equation by a vectorial equation, Hrgovčić replaces the scalar amplitude of the wave equation by four flux components that describe the field flux into and out of vertices in a quadratic lattice.

In this approach, the wave equation is replaced by a difference equation that operates on the dual lattice of a spatial quadratic lattice, i.e. on the vertices that connects lattice points with their four nearest neighbours. Let $\vec{r}$ be a point on the original spatial lattice, then the vectorial field $\vec{f}$ describes the four components of the field flux running into location $\vec{r}$ coming from the left, right, top and bottom neighbour. We write the four components as

$$\vec{f}(\vec{r},t) = \begin{pmatrix} f_{x,+} \\ f_{x,-} \\ f_{y,+} \\ f_{y,-} \end{pmatrix} (\vec{r},t) \quad \vec{r} \in \mathbb{Z}^2$$

keeping in mind that $f_{x,+}$ is the flux ingoing into the vertex at location $\vec{r}$ from its right neighbour, etc. Let $\vec{g}$ now the vector of the outgoing fluxes from vertex $\vec{r}$ to its neighbours, i.e.

$$g_{x,+}(\vec{r},t) = f_{x,-}(\vec{r}+\vec{e}_x,t) \qquad g_{x,-}(\vec{r},t) = f_{x,+}(\vec{r}-\vec{e}_x,t)$$
$$g_{y,+}(\vec{r},t) = f_{y,-}(\vec{r}+\vec{e}_y,t) \qquad g_{y,-}(\vec{r},t) = f_{y,+}(\vec{r}-\vec{e}_y,t)$$

then the following matrix equation describes the fluxes under the wave equation:

$$\begin{pmatrix} g_{x,+} \\ g_{x,-} \\ g_{y,+} \\ g_{y,-} \end{pmatrix} (\vec{r},t+1) = \qquad (2)$$
$$= \frac{1}{2} \begin{pmatrix} -1 & 1 & 1 & 1 \\ 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \end{pmatrix} \begin{pmatrix} f_{x,+} \\ f_{x,-} \\ f_{y,+} \\ f_{y,-} \end{pmatrix} (\vec{r},t) \, .$$

This equation is now finally suitable for its implementation in VideoEasel. For visualization efforts, it is also often useful to display the field amplitude directly: It is given as the sum of all four incoming fluxes; the intensity resp. the energy of the field is given as the sum of the squares of the components. It is now readily seen that the matrix in equation 2 is orthogonal, hence preserves the lengths of vectors, and by that also the energy of the field, as required. Some additional modifications not to be discussed here also allow the simulation of reflection on loose or fixed ends, and — as surprising as it may sound — even though the underlying lattice is clearly not isotropic, the simulation generates almost perfect spherical waves. Needless to say, as the equation is linear, the superposition principle holds, and effects like the construction of planar waves from spherical waves can be demonstrated. Examples will be shown in the next section.

IV. Experiments

In this section, a couple of typical experiments shall be shown to demonstrate the usefulness of the Virtual Laboratory. Fig. 1 demonstrates the linear superposition of two wave-fronts generated by two point excitations and the spherical wave created by an oscillator in the middle of the screen. The superposition principle is due to the linearity of the wave equation; in this simulation, linearity also only holds approximately because amplitudes of the excitation are limited; consequences from this limitation remain rather limited, though. It is further interesting to note that the generated waves are almost spherical, despite the simulation running on a square lattice.

The second set of figures (Fig. 2) demonstrates Huygens' Principle: A row of point-wise oscillators generates a wave-front that is almost planar by superimposing the spherical waves seen in Fig. 1. On the right hand of Fig. 2, a planar wave travels partially around a vertical obstacle, generating two spherical wave fronts behind the obstacle: This wave pattern can be understood by being generated by a vertical row of oscillators similar to that constructed in the first experiment, though interrupted by the obstacle in the middle. The oscillators at the top and bottom edge of the obstacle are then generating the spherical waves traveling into the "shadow" of the object which blocks the incoming planar wave. It is also interesting to note that the planar wave reflected back by the obstacle interferes with the incoming wave, forming a standing wave. Node lines become much more visible in the real animation than on the picture, though.

The third example shows the famous double-slit experiment (cf. Fig. 3): An incoming planar wave is blocked by a double slit, forming a typical interference pattern behind the slit. In a true-life experiment, laser light detracted at a double slit generates the very same pattern, becoming visible on a screen placed behind the slit. What is remarkable on this experiment is that a very similar pattern is also observable if the laser beam is replaced by a particle ray, quite contrary to common intuition. It is one of the elementary experiments in quantum physics. Following Huygens' principle, the very same interference pattern is of course generated by two oscillators placed at the position of the slits, as shown in the right-hand side of Fig. 3.

V. Integration of Virtual Laboratories and Remote Experiments into Lecture

The aim of LiLa is to share all the experiments participating institutions have to offer, enabling lecturers to select from almost unlimited resources for their lectures. The topic to be discussed in the following section is hence how to optimally integrate such resources into lectures, to mention potential challenges and how to overcome them, or in short, to give interested lecturers guidelines for optimal deployment of the LiLa material.

We are developing these guidelines again from our experiences using remote and virtual experiments in the lecture "Physics for Engineering", one example being the wave equation introduced in the sections above.

A. Initial Situation in "Physics for Engineering"

"Physics for Engineering" is a first year freshmen course taught to students of all kinds of engineering studies, including mechanical engineering, aerospace engineering and many others. Currently about 1300 students are attending the course. Due to the high number of participants and limited room capacity, lecturers are giving the same course twice a day, giving all students a chance to attend. The curriculum, recently modified to a Bachelor-Master study program, does not include any mandatory exercises for this specific lecture, nor does the tight schedule allow room for a mandatory lab course. However, experiences have shown that students participating in optional homework exercises handed out by the lecturer have a considerably higher chance passing the final written exam. Hands-on lab courses have not been part of these homework exercises, so far, however; the aim of this first pilot study is to offer students optional learning alternatives to the also optional pen-and-paper exercises.

The University of Stuttgart already offers an electronic Learning Management System (LMS) which provides information on the lecture, forums, questionnaires and material for self-study for this and many other lectures offered by the University. It is a well-accepted system known to both lecturers and students. Clearly, the LiLa experiments will be integrated into this system, here as applets running in a browser. This interactive content is then either used for self-study, or — in this starter project — in small student groups of at most 12 people a time, supported by teaching and technical staff of the physics department and the computing center.

We first performed an initial questionnaire to evaluate the motivation and interest of students in such optional courses, and to find out how much time they would have available for such additional courses. Around 87% are interested in participating in optional lab exercises, 23 % are willing to spend between half an hour to one hour for doing the exercise, 37,5 % are willing to spend one hour to one and a half hour and 30 % are able to spend one and a half hour to two hours. The remaining students may either have less than half an hour or more than two hours available for such courses. Apparently, the interest in such optional experiments is rather high, and the time students are able to invest into such courses is between half an hour and two hours.

B. Deployment Plan for the Exercises with Online-Experiments

The first step to do is to evaluate which experiments, virtual or remote, fit best into the content of the lecture. For that we

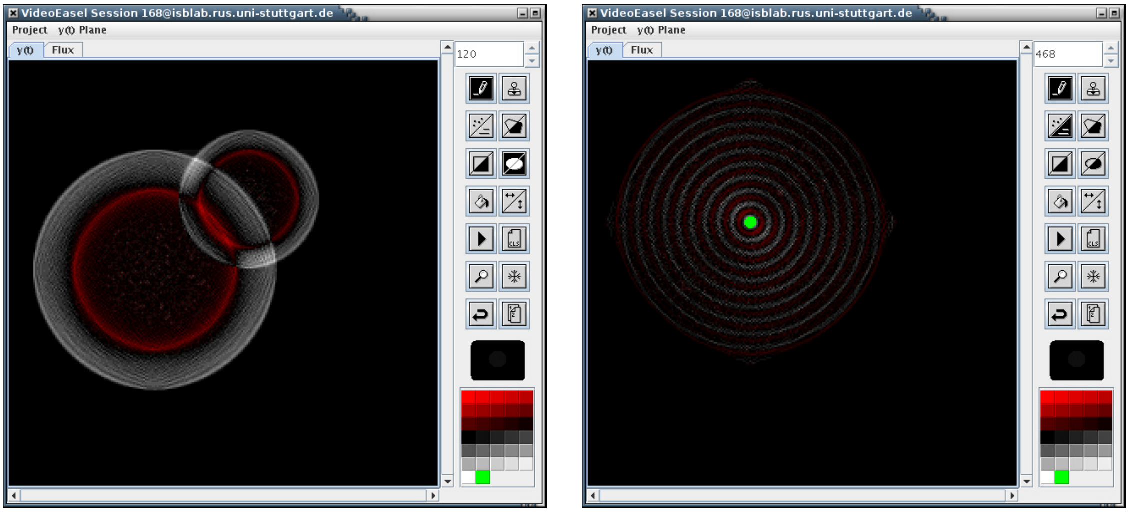

Fig. 1. Superposition of two point-excitations (left) and a spherical wave created by an oscillator (right)

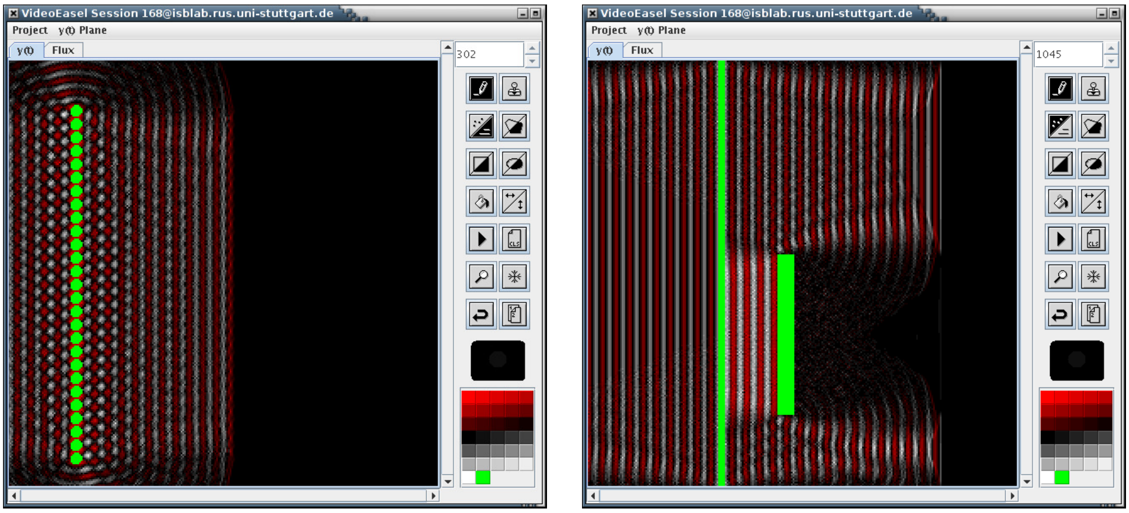

Fig. 2. Demonstration of Huygens' Principle (left), and a planar wave being blocked by an obstacle. Note that spherical waves travel into shadow of the obstacle.

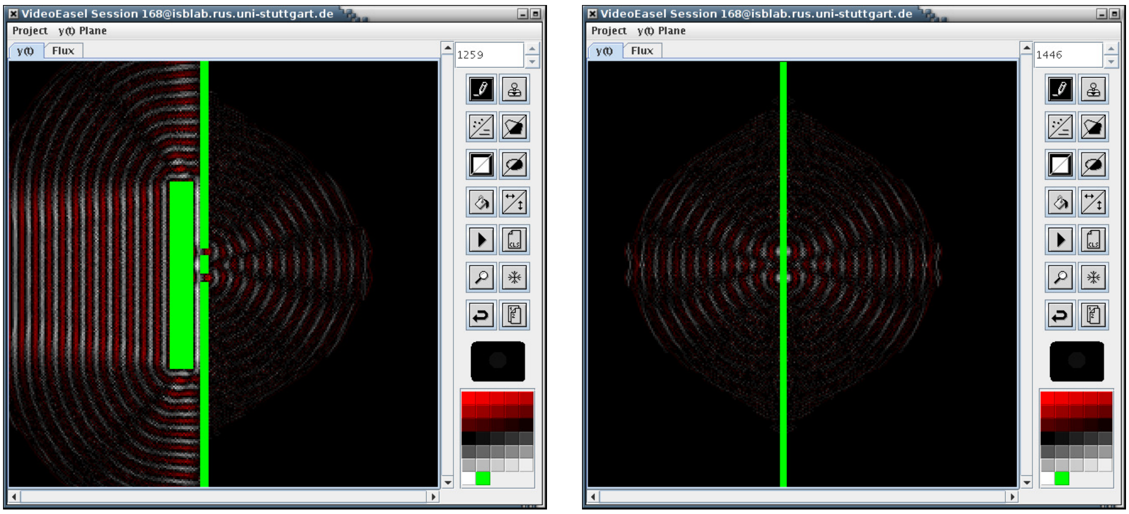

Fig. 3. The famous double slit experiment (left). The same interference pattern is generated by two oscillators replacing the slits (right).

compared the existing contents of the lecture with experiments available in Stuttgart and Berlin. For a first pilot phase we wanted to set up a manageable amount of experiments and decided to restrict the number of experiments to one per month.

Afterwards, we had to develop a structure for each of the experiments itself; this includes a both the organizational framework for the experiments as well as its technical realization which should fit into the Ilias LMS. We agreed on structuring experiments into the following three phases:

- **Orientation Phase:** This first phase allows students to familiarize themselves with the online experiment; an abstract on experiment is presented that contains a short description of experiment and the task to perform, the definition of the learning goals that should be reached, and a small pre-test evaluating the knowledge of the students.
- **Execution Phase:** This is the main phase of the exercise. Here the given tasks should be mastered by the students, i.e. running the experiments and measuring the results.
- **Review Phase:** The purpose of the last phase is to check the progress of the students. They pass again a small test, evaluating the knowledge obtained from running the experiment.

In the pilot, we also included an additional questionnaire in the review phase to gain some understanding on how students think about these exercises. Specifically, we want to know whether they believe to learn better with online experiments and whether their motivation looking into physics is increased by running experiments. Results of this questionnaire are not yet available and will be evaluated at the end of the winter term.

C. *Motivational Aspects*

Providing additional learning material helps little if students aren't motivated to use them; in this section, possible stimulations shall be discussed to optimize the impact of the provided material.

While providing experiments, and hence a chance to work actively instead of consuming content is a motivation by itself, realisticly speaking this type of motivation might only work for students that are intrinsically motivated already. However, freshmen are very busy and the course schedule for the first year is already very packed by lectures and courses of manifold kind. This leaves, unfortunately, only very limited time for *optional* exercises, and it seems also very unrealistic to change this situation in short-term; hence, we face a situation that makes it considerably hard to clarify the importance of additional work to be performed by students.

Currently, we consider the following mechanisms to build up an additional force to drive students:

- Students participating in online experiments gain extra points for the final exam at the end of the course. While in this strict sense legally problematic — an *optional* course element cannot become a requirement for passing the exam — a potential modification would be that points collected from running experiments are bonuses that can cancel errors made in the written exam while leaving the error thresholds for the grades otherwise untouched. That is, a 100 % error free exam would still count as an A grade, regardless of whether experiments have been performed or not, but a lower B grade could be improved by having participated in lab courses. Collecting bonuses for the exam is an already accepted and tested mechanism in other lectures.
  What might be problematic is testing students for continuous attendance of the lab courses; while less a problem for tutored courses, it is more a problem for students that use experiments for self study at home. The former type of student support remains, however, only available as long as we have funding from the LiLa project and might be not available beyond the pilot phase.
- An additional source for motivation might be the integration of a contest into exercises, asking students to provide answers or experiments for an open ended question. Such a question could be to provide an experimental setup that demonstrates interference of waves, or the relation of the strength of a wave from the distance of its origin, etc. At the end of the term the best student would be granted a price, e.g. a free iPod.
  Clearly, such a contest can never be completely objective or completely fair for the suggested open-ended exercises; results might be copied from fellow students as in exams, but we have a much less controlled environment here where chances for intellectual theft are considerably higher.

In our current planning, the wave equation experiment will provide a good framework for interesting open-ended questions to be posed that requires students to perform the experiments by themselves. The next section will propose a couple of exercises and questions we plan to provide. Unfortunately, results are not yet available at this time.

D. *Deployment and Scheduling*

In our current planning, the wave equation exercise is scheduled to the end winter term, following the schedule of the lecture; it is likely the last and final exercise in this course, and thus offers a good opportunity to state open-ended questions as mentioned in the paragraph above.

One of the challenges we have to face is the rather high number of participants; as mentioned earlier, we expect roughly 1300 students in the winter term. While we definitely hope that most of them will participate in our hands-on course, checking their solutions for correctness is a major hassle for a small team of assistants and tutors. We propose the following solutions to address this problem:

- Automatic testing of results by the Ilias learning management system. This requires, of course, that exercises are stated in a way that allows automatic testing, e.g. by requiring students to find a numeric value by measuring a phenomenon, or by stating multiple-choice exercises. A potential exercise here would be to ask students to measure the amplitude of a spherical wave as a function of the distance from the oscillator; it can be seen from the explicit solution above — or by considering the conservation of energy — that the amplitude must decay as $1/r$. Since our laboratory also includes a SCORM integration, such exercises could also be stated within the laboratory system itself, forwarding any measurement results directly to the Ilias system.

- Peer reviewing. Here experimental setups created within a small group of students, say two to three, are reviewed by a second, independent team. Each group would have to prepare a report about their findings and experimental setups which is then checked by peers. A possible task would be to design an experimental setup demonstrating Huygens' principle and report on the results.
- As a modification of the above ideas, small modifications of the same assignment could be handed out to individual students instead of student groups; alternatively, combinations of the ideas above are possible were a first student group built the experiments and a second group checks for proper results and enters the measurement results into the Ilias system.

The aim of all exercises is of course to ensure that students gained insight into the wave equation while keeping them motivated to participate. Peer reviewing imposes the risk of students dismissing reports from their fellow students, or creating unfair review results due to varying background knowledge at the reviewers themselves. However, it also creates an additional learning effect by requiring student reviewers to go over the material once again. At this time, we do not yet know whether our ideas will work and we cannot yet present results, however, we surely never find out without trying. First experiences will become available end of the winter term.

VI. Results and Future Prospects

While we haven't had the chance to use the virtual laboratory for students, we nevertheless already run an initial test-case with a simple flash-based experiment created by the University of Colorado [8], and used here as a "warm up"; about 250 of 1300 participated in this test case, but the first results look very promising: A first analysis of the online-questionnaire shows that around 90% of the students enjoyed the exercise with an online-simulation. Also around 90% of them stated that they are more motivated to deal with the content of the lecture due to the online-simulation. Around 85% were thinking that their learning success will be higher with doing these exercises. For around 90% of the participants the content of the exercise was easily comprehensible.

Unfortunately, instructions how to handle the online experiment were not yet sufficient; about 45% reported insufficient instructions, requiring us to enhance the descriptions and being more precise on the expected tasks. For example, we gave no information how to round the numerical results, and the Ilias system was not flexible enough to accept results rounded to a different number of digits than we expected, causing it to rate some of the results as incorrect, and hence demotivating students. Of course, once we would have built up a working and tested corpus of online experiments, such problems will be avoided; what we should learn here is, however, not to underestimate the effort that needs to go into testing.

Exercises were accompanied by online questionnaires to be filled out by students using the exercises for self-study; additionally, we were able to reserve work-stations for groups of twelve students in the computer department on campus, allowing them to meet with tutors and experts to help them with their tasks. While it is unclear whether we will be able to offer on-site help in the future, it did allow us now to interview the participants directly, and we will be able to report our findings at the end of the term as soon as the data is collected and analyzed.

Concluding, we hope to be able to enrich the engineering studies by providing exciting, entertaining and instructural experiments students are able to perform at home any time they like; however, as we have already seen, providing just the experiments themselves is insufficient: they need to be embedded into a pedagogical strategy and must be complemented by sufficient instructional material telling students what the experiments are about, how to perform them, and which results we are expecting from them.

VII. Acknowledgments

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