On Remote and Virtual Experiments in eLearning

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Abstract— The science of physics is based on theories and models as well as experiments: the former structure relations and simplify reality to a degree such that predictions on physical phenomena can be derived by means of mathematics. The latter allow verification or falsification of these predictions. Computer sciences allow a new access to this relationship, especially well-suited for education: New Technologies provide simulations for the model, virtual instruments for running and evaluating real experiments and mathematical toolkits to solve equations derived from the theory analytically and to compare the outcome of all three methods. We will demonstrate this approach on several examples: Ferromagnetism, thermodynamics and the Harmonic Oszillator. We furthermore give a brief example on an online-tutoring system that makes our setup attractive for self-study outside the university campus.

I. Introduction

One of the intellectual challenges when learning physics is to understand the role of a physical theory, the role of a physical model and the role of an experiment. Often, these terms are intermixed, and the curriculum separating lectures into theoretical and experimental physics does not make it easier to comprehend their interrelation.

Modern eLearning technology may act as a bridge: On the one hand, computer systems make real experiments available over the Internet, any time, anywhere, and — even more important — make the measured data electronically available for further analysis. On the other hand, a *model* for an experiment can be implemented as a simulation within a virtual laboratory, making the same physical quantities available for measurement as in the "real" experiment. Both support pervasive learning in providing ubiquitous access to experimental setups and even access to experiments too complex, dangerous or expensive. It is now straight forward for a student to compare the outcome of the two approaches and to compare them again with an analytic result of a physical theory. Thereby, similarities and differences between the theory, the model and the experiment can be demonstrated and analyzed. Remote experiments and simulations are actively used in various experimental sciences, related training courses have also been explored in chemistry, see e.g. [1] and electrical engineering, e.g. by [2]. However, the relation between experiment and simulation is rarely stressed. The combination of complementing virtual labs and remote experiments supports the analysis of a given physical phenomenon from different angles. The capability of remote access through the Internet allows the student a *direct* comparison of theory and model on one hand and experiment and physical reality on the other without having to switch back and forth between library or Internet and the laboratory. An interesting and related setup is the remote experiment and virtual lab for wind tunnels developed by Esche et al. [3], a virtual laboratory for exploiting DSP algorithms [4], and a learning tool for chip manufacturing [5]. Virtual labs are also explored as on-shore educational tool to train the technical skills of sailors of the US navy, see [6].

Thus, besides the pedagogical advantages, eLearning offers the possibility to make the learning environment available anytime and from anywhere, and due to course management and electronic tutoring, even in the absense of any teaching staff; our framework is intrinsically net-worked and allows students to access the experiments online, either by the campus-wide WLAN access, or from outside the university by the Internet provider of their choice. Due to a grant made by Hewlett Packard, we are also able to provide students with a limited amount of tablet PCs within the classroom [7], access to the computer lab is thus not a requirement. The integration of tablet PCs into education opens up new perspectives and allows to increase the experimental part of the education right from its start. Executed within web-interfaces, experiments can be implemented and accessed regardless of location of laboratory and experimenter. Additionally, experiments can be performed which otherwise would not have been accessible for reasons of expense, security, or availability.

In this work we present three examples for the combined use of virtual and remote experiments in the universitary education of engeneering students. The interplay between these eLearning environments allows us to overcome the predominant separation between theoretical courses on one hand and existing practical courses on the other hand. In our virtual laboratories models with an increasing amount of complexity adjusted to the students learning level can be used to circumstantiate the

experimental results. Hereby training very important skills like *e.g.* the abstraction from the simmulation and from the experiment to understand the relation between them. This type of understanding – beeing able to discuss real systems from an abstart view-point to apply the knowl-edge from *ad hoc* different setups – is elementary in all natural sciences. We come furthermore to the conclusion, that our inteligent tutoring system ("Marvin") can greatly improve the learning success of each individual student by considering the useres learning behavior.

This paper is organized as follows: We first discuss three important physical systems and demonstrate our approach on them: First, the physics of ferromagnetism and the Ising model as a prominent system of statistical mechanics in section II. Second, the physics of ideal gases and the corresponding lattice gas model [8], [9] in section III to discuss the concept of entropy phenomeno-logically as well as statistical thermodynamics. Our third example in section IV is a true classic, the Harmonic Oszillator. We will argue in each section how the *comparison* of the experimental access and the simulation made possible by using networked technology provides new pedagogical advantages and facilitates pervasive learning. Finally, in section V we give a very brief introduction into our electronic tutoring system [10] that enables students to even run complete courses within this framework for self-study in the absense of teaching staff. We close with conclusions and an outlook for future work in section VI.

II. BRIEF INTRODUCTION TO MAGNETISM

Materials react differently to an applied external mag-netic field: they are either diamagnetic, paramagnetic or display effects due to the correlations of magnetic mo-ments in the material, such as ferromagnetism or antifer-romagnetism [11]. Diamagnetism and paramagnetism are weak and require relatively large external fields to make them visible. Ferromagnetism, however, is apparent even at small external fields: Unlike dia- and paramagnetism, it is a many-body phenomenon where the elementary magnets of an otherwise paramagnetic material interact with each other and couple their magnetic moments such that a macroscopic field is generated. The *magnetization* M of the elementary magnets in the material adds up with the external *magnetic field* H to the *magnetic induction* B.

Two properties are characteristic for M for ferromag-netic media: First of all, there is no unique relation between H and the induced magnetization M, but M depends on the history of the process. Ferromagnetic ma-terials show a *hysteresis*, and a plot of the magnetization over the magnetic field has a typical double-S shaped form (see Fig. 2). Second, the ferromagnetic effect vanishes for high temperatures: If the temperature T becomes larger than the *Curie-temperature* T_c, ferromagnetic materials become paramagnetic and the hysteresis vanishes, thus establishing a *phase transition*. Ernst Ising developed a microscopic model to explain ferromagnetic behavior in the 1920's. According to which ferromagnets consist

of elementary magnets called *spins*, carrying magnetic moments — in the simplest possible model — pointing into one of two possible directions. They interact with their nearest neighbors in such a way that the energy contribution of a spin-spin pair to the total energy is minimal if the two neighboring spins have parallel mag-netic moments, and maximal if they are antiparallel. Even though Ising's first attempt to show a phase transition in a one-dimensional spin-chain failed, a two-dimensional model did reproduce all macroscopic effects. A rigorous proof of ferromagnetic behavior within this model was given by Onsager many years later [12].
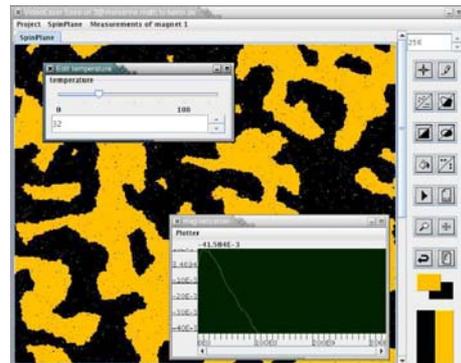

Figure 1. The Ising Model in the virtual lab VideoEasel

A. Magnetism in Virtual Laboratories

The *Virtual Laboratory* VideoEasel developed at the TU Berlin focuses on the field of statistical physics and statistical mechanics [13], [14]. Implementing a freely programmable cellular automaton [15], VideoEasel is capable of simulating various models of statistical me-chanics and related fields.

Technically, VideoEasel is a client-server architecture with a C++ based number cruncher running on the server that implements a programmable cellular automaton [15], and Java clients that communicate to the server through CORBA [16] middle-ware providing a remote function call interface. As a result, networked access to a labora-tory session running on VideoEasel works seamlessly, connecting through the campus wide wireless network of our university. For online and demo experiments, a simplified version of the Java client is available as an applet that runs in a browser; unlike the former setup, which mainly targets to provide hands-on training for students, the applet interface has been made as simple as possible to gain access to experiments in lectures or web-presentations.

The virtual laboratory can be programmed freely at runtime, to simulate every statistical system of interest, let it be by the student, or by the teacher. For that, a C-like programming language sets up the local computation rules of the automaton, defines parameters later on made accessible by the user interfaces and boundary conditions, etc. To lower the access barrier, many experiments are

already hosted at the server and do not require manual setup, but a user is always free to use them as a basis for his own experiments by modifying the code in his local session as needed. The modified code is then transmitted back into the server, compiled, and linked into the server at run-time.
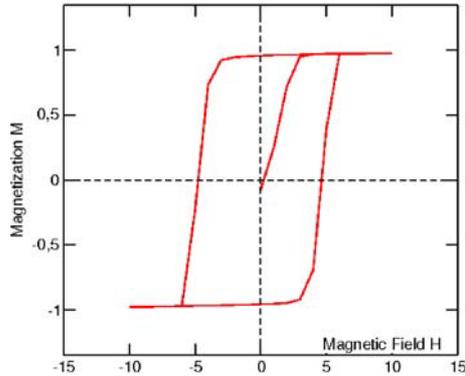

Figure 2. Hysteresis loop of the Ising model

The CORBA interface also makes it possible to share a laboratory session amongst several students, or a group of students and an administrator: A user is free to "publish" a laboratory session under a password, allowing other users to hook into this setup. Even though originally considered for collaborative learning, it also helps the administrator of a course a lot to help students online by linking into their session [13]. Clearly, due to the networked architecture, students can share sessions from anywhere in the Internet.

Measurements within the laboratory are performed by algorithms that are plugged into a running experiment as needed, allowing to observe magnetization, entropy, free energy or other measuring quantities. Similar to the simulations, measurement devices are also represented by cellular automaton code that can be either written by hand, or loaded from the server. The code is then compiled and linked into the experiment at run-time, and delivers its measurements to the graphical front-end over the network. When experiments of higher complexity are performed, the experimental results can be automatically exported into computer algebra systems for further analysis; this interface just uses the already available CORBA calls to gain access to the measurements in the laboratory core.

To investigate the Ising model, VideoEasel implements the *Metropolis* dynamics [17], see Fig. 1: Spins are selected at random and flipped if either the overall energy of the model decreases after the flip, or the energy can be borrowed from a heat-reservoir. The user is able to control the temperature T and external field H over parameters exported by the code, and then measures quantities like the magnetization M. If we plot the relation between M and the field H for low temperature, a hysteresis loop is found, see Fig. 2. For high temperatures this figure vanishes. Since collecting the data by hand is a time-consuming task, we automated this process for the purpose of this paper and used Maple to control the lab-

oratory and plot the hysteresis curve for us. Additionally, our model allows us to measure an additional parameter, namely the *Helmholtz Free Energy F* [18]. This quantity is phenomenologically defined as the fraction of the overall energy of the model that is available for mechanical work.

We also run the very same experiment in class asking our students to measure M and F within the laboratory, see Fig. 3 for a typical result. Students almost immediately conjectured from the plots that M must be proportional to the negative derivate of F with respect to H. After having seen that, our students easily derived this from the *Gibbs state* of the Ising model [18], and thus our experiment was also didactically successful.
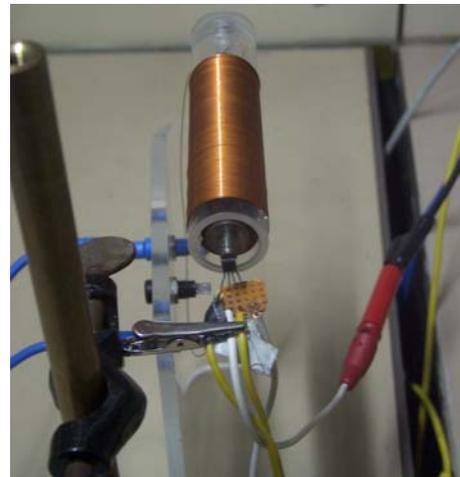
B. Hysteresis in Remote Experiments

Figure 4. Setup of the remote experiment on hysteresis, the magnetic coil in the middle, Hall probe in front

Complementary to Virtual Laboratories, *Remote Experiments* are real experiments, remotely controlled by the student from outside the laboratory. A Remote Experiment consists of two basic parts, namely the experiment itself and a computer interface allowing control over the experiment via the Internet. For the latter, we use National Instruments LabView [19]. In order to view and control the experiment, a freely available web browser plug-in has to be downloaded and installed, and thus the experiment becomes available in every browser, quite similar to the Java applet of the Virtual Laboratory. Due to the modular programming structure of LabView, remote experiments can easily be combined or extended [20], though unlike the virtual laboratory, the experimental setup itself has to remain fixed.

We can now run the same experiment, namely that of measuring the hysteresis loop of magnetization vs magnetic field, in reality: a magnetic coil generates a magnetic field H that is proportional to the current passing through it, which is controlled by the computer. The magnetic field magnetizes a ferromagnetic core. The Magnetic induction B is measured by a Hall probe, see Fig. 4. The measured
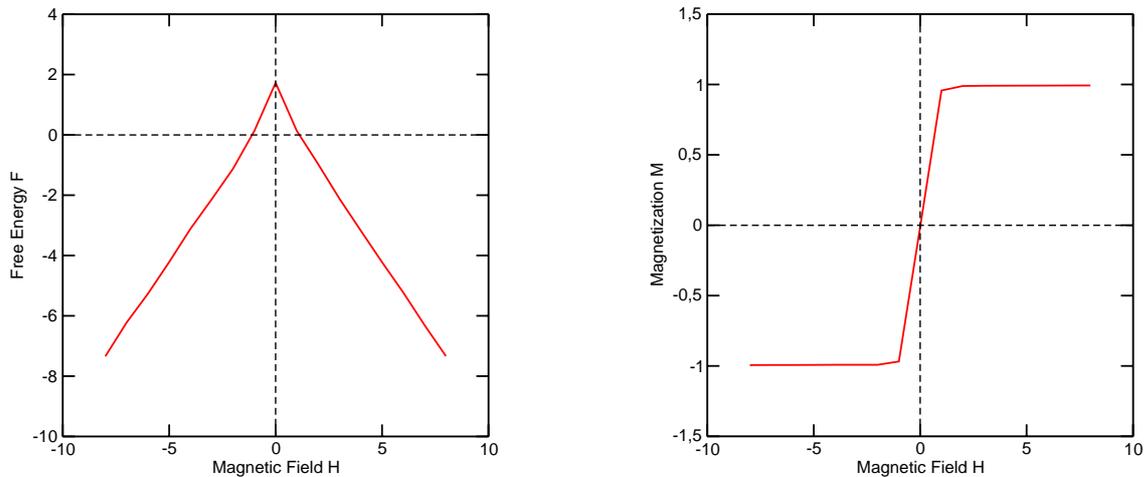
Figure 3. Free energy(left) and magnetization(right) as functions of the external field

value is then digitized by an analog-digital converter that provides a digital output port, and by that made available to the computer system.

C. Virtual Laboratories & Remote Experiments: Similarities and Differences

At first glance, both the experiment and the model show the same hysteresis effect: the relation between magnetization and magnetic field cannot be represented by a function. However, a student running both types of experiments will note that the exact shape of the hysteresis loops is very different: Whereas the Ising model shows an almost rectangular shape, cf. Fig. 2, textbooks typically show an S-shaped form. But even the usual graphs found in textbooks do not always depict reality correctly: The hysteresis loop only encloses a very small area, see Fig. 5. Thus experiment and model do not agree completely. There are also deviations between model and theory: When taking the numerical derivative of the free energy, the curve looks almost, but not quite like the magnetization plot: The derivations are best seen for small fields.This is likely because our entropy measurement is only an approximation and does not take long-range interactions into consideration. Students, in this way, learn that models are by their very nature incomplete, and theories make approximations and can only predict reality within a certain error. The advantage of having both the real experiment as well as the simulation available over the Internet is that students have now the freedom to compare the outcome of both experiments side by side; the traditional approach would have been to discuss the Ising model in a higher mathematics or theoretical physics lecture, and the ferromagnetism in an experimental physics lecture. Details like the shape of the hysteresis curve are then likely to be overseen

and the differences between simulation and experiment remain ignored. Thus, networked technology does not only allow students to learn from anywhere at any time, it also enables us to provide different perspectives to the same physical phenomenon simultaneously. The different role of experiment and simulation becomes even more apparent in our next example.
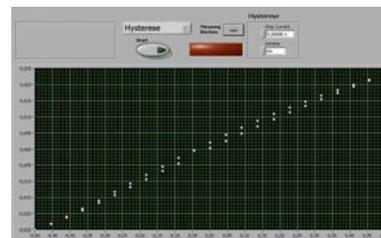

Figure 5. Hysteresis loop as found in the remote experiment

III. BRIEF INTRODUCTION INTO THERMODYNAMICS

Thermodynamics is the physics of temperature and heat. As a phenomenological science, it formulates the relations observed between physical observables. For example, the product of the pressure and volume of an ideal gas is proportional to its temperature. However, it does not attempt to derive these relations from a microscopic theory.

Even though these relations are obvious to verify in an experiment, thermodynamics also formulates laws that are harder to relate to experiments. The most prominent example is the second law of thermodynamics, first formulated by Clausius [21], which states the existence of a thermodynamic potential called the *entropy*, which cannot increase in closed systems. One of the consequences of this law is that thermodynamic processes, e.g. combustion

engines transforming heat into mechanical work, must have a limited efficiency strictly below 1. Said another way, it is impossible to convert heat energy into mechanical work without any loss [18] for temperatures $T > 0$.

Since entropy is a rather abstract concept that cannot be measured directly, this law is, almost traditionally, hard to motivate to students. Some textbooks even joke that "students usually only believe this law because they wouldn't otherwise pass their exam".

A. Phenomenological Thermodynamics in the Remote Experiment

To demonstrate the classical gas laws, our remote experiment farm also includes an experiment on thermodynamics, see Fig 6. A motor controls the position of a piston in a glass cylinder containing air whose temperature can be remotely adjusted by a heater. Sensors measure the pressure of the gas and its temperature. Their measurements are digitized and made available over the Internet. Given this setup, students can readily verify the classical laws of phenomenological thermodynamics, for example the Gay-Lussac relation between volume and temperature.

Figure 6. The remote experiment for phenomenological thermodynamics. A piston (top) runs in a glass cylinder compressing air. The temperature of the gas can be adjusted by a header (bottom) and the pressure and the position of the piston are measured.

However, one can clearly go beyond this experiment: By controlling the heater and the piston, students can run the system in a thermodynamic cycle process. The amount of heat energy induced is known due to the characteristics of the heater, and the amount of mechanical energy made available by a cycle can be computed from the area within the pV diagram [11] as measured, see Fig. 7. Comparing the two readily presents the limited effectiveness of the process, and demonstrates one of the consequences of the second law of thermodynamics.

B. Lattice Gases in the Virtual Laboratory

Lattice gases are simple, discrete models for ideal gases defined as cellular automata [15], and as such
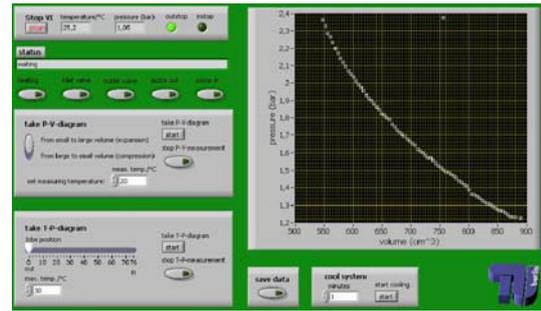

Figure 7. The pV diagram as measured in the remote experiment.

easily implementable in our virtual laboratory. Within the HPP model used by our setup [8], [9], the gas consists of elementary particles, atoms called in the following, which can only travel in four diagonal directions within two-dimensional space. Collisions with boundaries and between atoms preserve energy and moments, see Fig. 9.
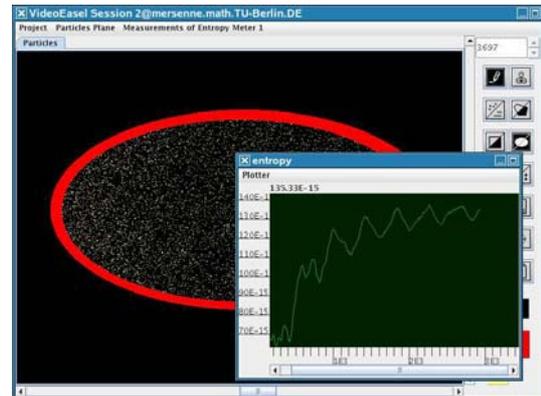

Figure 8. Final state after running the HPP gas for some time, incl. plot of entropy over time.

Unlike in remote experiments, we are now in a position where we know the microscopic state of the system exactly, and are thus able to measure the entropy. In a simple experiment, a student fills one corner of a simulated gas container with the lattice gas. If the simulation is run, the gas expands into all of the container and the entropy increases except for some small derivation, see Fig. 8. The monotonicity of the entropy looks even more surprising if we recapitulate that the elementary laws of the HPP gas are completely symmetric in time: If we invert the moments of the gas atoms in the first row of Fig. 9 and read the figure from right to left, we also get a possible motion.

The very same argument has been considered historically by Loschmidt as an objection against Boltzmann's H-Theorem [22], [23]: Students are now, however, in a position where this objection can be discussed within an experiment, as our virtual laboratory provides means to invert all momenta. Quite as one might expect, gas atoms then move back to their initial positions and the entropy function decreases.

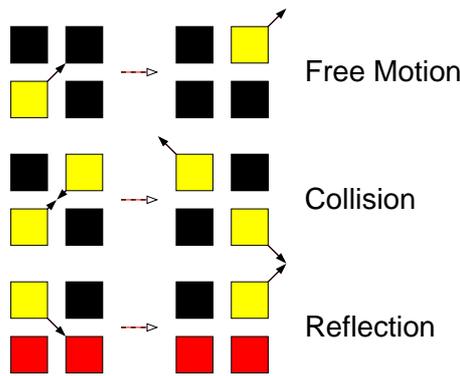An experiment whose outcome is confusing is well-

Figure 9. Elementary rules of the HPP gas: Gas atoms (yellow) travel with constant velocity along diagonal directions. Upon pairwise collision (middle row) they reflect under a $90°$ degree angle. When colliding with the boundary, they reflect perfectly (bottom row). All other rules follow from rotation and reflection.

Figure 10. A pair of coupled linear oszillators.

suited to stimulate a vibrant discussion amongst our students. The resolution is now that the initial state of a gas running back into its container is extremely unlikely and with some guidance, students often come up with an experiment to justify this argument: After modifying the seemingly chaotic state by displacing a single atom by one pixel, we invert the moments of all gas atoms again and observe the entropy and the system behavior again. Even though the entropy starts to decrease for a short while, the system comes no longer close to the initial minimum, and entropy begins to increase shortly after.

C. Comparing Remote Experiments and Virtual Laboratories

It is worth noting that the pV looks again not very much like the idealized curves found in textbooks and is rather noisy. Good textbooks will of course comment on such peculiarities. Similar differences often arise in real experiments, as we already found for the hysteresis experiment. They need to be discussed with the students and make up an important part of the education in physics, too. On the other hand, we also find a tiny discrepancy between the phenomenologically formulated second law of thermodynamics and the corresponding outcome of the virtual experiment: It is not impossible that the entropy decreases, it is just that all odds are against it. Thus, the important lesson to be learned is that the second law makes a statement about the statistics of the system.

The complementary nature of remote experiments and virtual laboratories becomes even more apparent for the experiments on thermodynamics: While the remote experiment is targeted at the phenomenological side of thermodynamics, virtual laboratories allow to explore the statistical mathematical aspect of entropy. Thus, the dual nature of thermodynamical variables such as entropy — being a phenomenological quantity as well as a statistical one — can be explored and demonstrated.
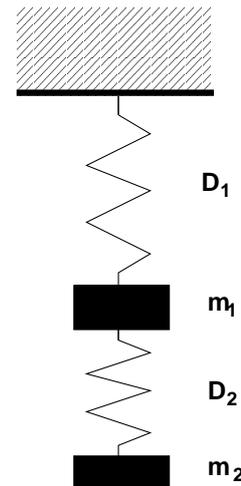
IV. THE COUPLED HARMONIC OSCILLATOR

The harmonic oscillator is probably the most often discussed physical system of all times; it is described by a simple linear differential equation of second order whose solutions and behaivour is discussed in the freshmen courses. Despite its simplicity, the properties of this system are needed in all branches of physics because its equation is often found as the linearization of more complex, non-linear differential equations that cannot be solved in closed form. Thus, the solutions of the harmonic oscillator equation are good approximations of complex phenomena for small amplitudes. The important lesson to learn here is being able to abstract from a *concrete physical setup* and understand the phenomenon on an abstract level, thus to relate the behaivour of systems that are, at first glance, different.

The next pair of experiments we describe here stresses exactly this point of view on a slightly more complex setup, namely that of the coupled linear oscillator. One physical realization of this system is shown in Fig. 10: A spring with Hook's constant D_1 is attached to mass m_1, which is again attached by a second spring D_2 to mass m_2. If we impose Hook's law, namely the force of the spring is proportional to its extension, one can describe the system as a coupled two-dimensional linear system of differential equations. To get a more realistic model, we also include the effect of friction in our simulation that damps the oscillation.

The mathematical solution of this linear system now shows the following property: If the damping (i.e. friction constant) of the oscillators is very different, then after a short while the oscillator with the smaller friction determines the motion of the overall system. The movement of the mass attached to the spring with the higher friction just follows the second mass after a while, and its movement is larger the closer the frequencies of the two systems get.
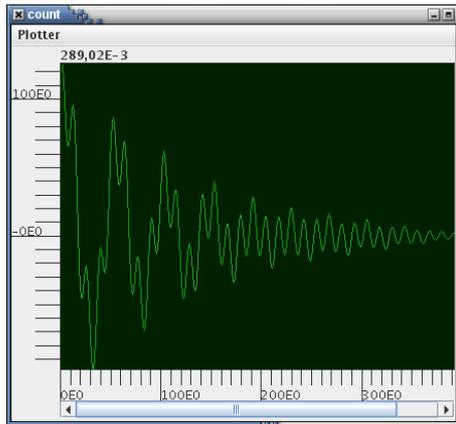
Figure 11. Plot of the amplitude of one oszillator from a coupled pair over time.

A. The Coupled Oscillator in the Virtual Laboratory

Our Virtual Laboratory includes an experimental setup to simulate the coupled harmonic oszillator of Fig. 10. The amplitude and velocity of each of the oszillators is encoded in colors, and a plotter can be attached to the setup to measure the amplitude over time and to convert the colors into a more readable plot. The laborarory setup can be tuned by lots of parameters describing the friction, masses, springs and coupling between the two oszillators.

The outcome of a classical experiment is shown in Fig. 11: The frequency of the first oszillator is lower than that of the second, but its damping is higher. Thus, after the first couple of oszillations, only the faster and less damped oszillation remains.

This is also a classical result of linear differential equations: An external force is mathematically represented as an inhomogenity of the corresponding differential equation. The general solution of this equation is given as the sum of the homogeneous solution, the fast-decaying slow-frequency oszillation, plus one solution of the inhomogeneous problem, namely the fast oszillation of the exteriour force.

Thus, it seems that our virtual experiment represents the mathematics quite adequately. However, this is only partially the case, as for all other experiments discussed here: Note again that our experiment is based on a cellular automaton, and hence is discrete in time and the number of states. The differential equations are thus modeled by difference equations over a finite set. Luckely, it can be shown that the solutions of each linear differential equation with constant coefficients can be reproduced by solving a suitable difference equation, which is what is done by the simulation. The parameters required to reproduce a specific behaviour, e.g. damped oscillation, are, however, not identical to that of the difference equation.

B. The Coupled Pendulum in Physics

A second prominent example of an oszillator is of course the pendulum, and similar to the setup in Fig. 10, one can couple two of them by a spring to discuss the

Figure 12. The physical setup for the coupled oscillator.

properties of coupled systems, arriving at the physical setup of Fig. 12:

In our experiment, the angles of the two pendula are measured by potentiometers and thus made available to the computer. Furthermore, the position of the spring and thus the strength of the coupling can be adjusted by step motors that are also under control of the computer. Additionally, one can adjust the initial extent of the two oscillators.

At first glance, this system looks very much different from the simple coupled springs in Fig. 10: The two springs are replaced by two pendula, and the coupling is realized not by attaching one spring to another, but by an additional horizontal spring between the two arms. Thus, three, and not two systems are coupled here.

In an experiment, one could for example extend one pendulum while leaving the other in its rest position, and then let the setup move freely. The amplitude of the pendula over time for this initial condition is depicted in Fig. 13. As one can see from the plots, the amplitude of the first pendulum decreases shortly after the experiment has been started while the second pendulum starts to swing. Then, shortly afterwards the situation reverses again and the energy is transfered back from the second to the first. This continues on and on until friction stops all movements.

C. Comparing the Systems

At first, neither the setup in Fig. 10 seems to be related to the experimental setup shown in Fig. 12, nor look the plots very much alike. To really understand the relation of the two systems, it should be noted that the virtual

Figure 14. Plot of the amplitude of the simulated system with parameters adjusted to fit the coupled pendula.
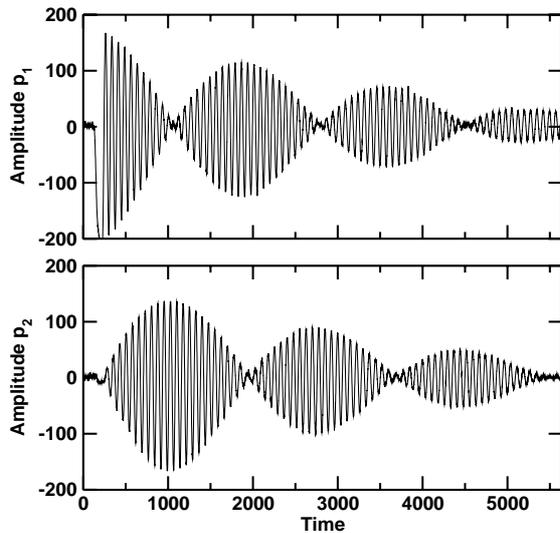

Figure 13. The amplitude of each pendulum in the coupled system over time. The initial condition placed pendulum 1 (top) at the amplitude 200 while leaving pendulum 2 in its rest position. Units are arbitrary.

laboratory simulates a *system of differential equations*, namely one whose solutions describe the amplitudes over time of the physical system. However, the very same differential equation, just with different parameters, also describes a lot of other systems and is not restricted to coupled springs. Hence, some mathematics is required at this point to really understand the relation between the two systems.

It turns out that the movement of the physical system is actually the solution of the very same system of differential equations. Even though we have three coupled systems here, only two degrees of freedom exist — namely the angles of the pendula — and thus a coupled system of two differential equations as in the virtual laboratory is sufficient. Since this is the general class of equations simulated in the virtual lab, it should be possible to define its parameters in such a way that it reproduces the physical behaviour of the system in Fig. 12 and not only that of Fig. 10. This is, indeed, the case — the plot of the corresponding simulated system is seen in Fig. 14.

This pair of experiments stresses the importance of mathematics as key-technology: A proper level of *abstraction* from the simulation and the experiment is required to understand the relation between the two systems, and once this abstraction has been made, the relation between the systems becomes obvious. However, this type of understanding — being able to discuss real systems from an abstract view-point to apply the knowledge from *ad hoc different* setups — is elementary in all natural sciences.

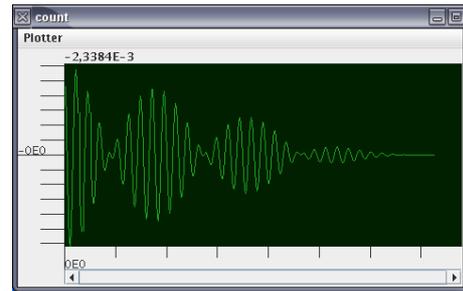The virtual laboratory setup is of course more flexible

by also providing additional experiments for important *mathematical* phenomena, e.g. the way how solutions of inhomogeneous differential equations look like, but experiments within a computer also require a higher level of abstraction.

V. COURSE SYSTEMS FOR VIRTUAL LABORATORIES AND REMOTE EXPERIMENTS

Since Virtual Laboratories and Remote Experiments are controlled from a computer system anyhow, it is an obvious step to try to embed both into a course system. The aim of those systems is not to replace lectures or traditional hands-on training, but to provide an easy access to complex matters by delivering some guidance for the students and to support pervasive "off-shore" learning in the absense of a teacher.

Our virtual laboratory is currently equipped with a tutoring system called "Marvin": Within this system, a course is built from so-called "asset nodes", each of them defining an elementary step to be performed by the user as part of a more complex experiment. Typical steps would be the setup of a random spin configuration of the Ising model introduced in section II-A or the definition of proper parameters for the harmonic oszillator as demonstrated in section IV-A. The user behaviour, e.g. whether a student has performed a given asset, or to which degree an asset has been managed, is observed by so-called "evaluators", tiny snippets of java code that are loaded into the laboratory at run-time and that have access to core-components of the laboratory. Depending on the outcome of this evaluation, the tutoring system selects the asset to branch to, for example to provide additional help to the student or to move on in the course. An evaluator is for example able to check whether a student really selected the "Fill" tool of the laboratory and defined a proper fill-mode to setup a random spin configuration for the Ising model [13], [24].

The combination of evaluation points and asset nodes thus defines a network, classically rendered as a flow-chart as in Fig. 15, that defines the "storyboard" of the course. The idea of using flow charts to describe learing pathes goes back to the early days of computer-supported learing, cf. [25]–[27].

It is, however, often not desirable to use the decisions of the evaluators directly to define a target asset node. First
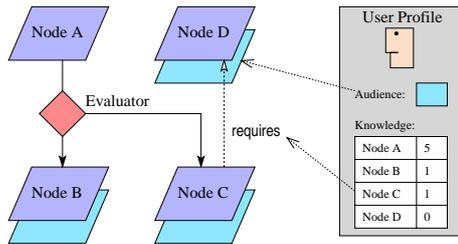
Figure 15. Storyboard and user profiling for automatic tutoring systems. Asset nodes (blue) may exist in several copies (varying tones of blue) that differ only on the target audience, evaluators (orange) branch between them. In addition, nodes are indirectly linked by requirements between them.

of all, this type of "hard link" within the storyboard makes courses unflexible because the system will react always the same way given a certain type of input, regardless of the student and his or hers background. Second, it prohibits re-using course components for other courses as links do not remain intact when moving a node out of its course.

For that purpose, "Marvin" also provides a different type of linkage: Each node or group of nodes defines a learning goal it provides. Additionally, each node also defines a couple of pre-conditions, i.e. material that must have been learned prior entering the node at hand. The tutoring system is now able to resolve the requirements at run-time by checking thru the node database and selecting asset nodes satisfy the requirements and thus fit to the prior knowledge of the student. Since links are now not performed by assets, but rather by learning content, a group of assets providing one specific learning goal can be simply copied into a different course.

The sub-graph formed by the requirement links is also called "Hasse Diagram" in educational sciences, and similar techniques have already been deployed earlier, for example by [28].

Furthermore, each node also defines an "audience", allowing several nodes providing similar contents just targetted at students with varying background. That is, the course system is by that also able to adjust to the background of the student, for example to address differing notation conventions used for the same object depending on the field of the study.

Simple optimization strategies exist that, under a suitable probability model, optimize the expectation of the learning success. It is beyond the scope of this article to discuss the details, the reader is refered to [10] for more information on the tutoring system itself.

VI. CONCLUSION AND OUTLOOK

The accomplishment of experiments in eLearning scenarios touches many aspects — ranging from the actual quantification of a physical measurement over operating experience with real experimental setups to the examination of the corresponding theoretical model — of the learning process in the academic education of natural

and engineering scientists. The combination of real experiments with virtual laboratories creates many benefits, of which the most important is that we allow students to study a physical phenomenon throughout experiment, model and theory. We believe that the complementary nature of remote experiments and virtual laboratories stimulates the process of *understanding* in an outstanding matter, which is vital for the learning process in natural sciences.

In addition, both virtual laboratories and remote experiments are well-suited to support pervasive learning. The client-server-architecture of the virtual labs allows running even complex experiments with a high demand on processing power from small mobile devices, while the Java plug-ins provide flexibility in terms of supported operating systems. Similarly, remote experiments provide hands-on experience in experimentation without requiring physical access to the set-up. Scientific experiments are made independent of the respective locations of learner and set-up, and can be made accessible 24/7 as long as the servers running the virtual lab or controlling the remote experiment are online. Truely pervasive deployment of the experiments for learning and teaching purposes are possible due to a modern online-course system that interacts directly with the laboratory core to observe user behaivour to optimize the learning performance.

Our work will also continue into another direction, namely in trying to perform experiments where virtual and real components interact, for example to compare their outcomes in a common plot within Maple, the mathematical algebra program.

The tutoring system described in section V is currently restricted to the virtual experiments, but since it is otherwise a generic Java program that interfaces to the learning management system only by external interface classes, it should be possible to equip the remote experiments with an electronic on-line tutor, too.

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