Ph.D. Thesis

Application of Computers in the BSc-level Modern Physics Education

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Introduction

In undergraduate-level education, the physics subject has a role of providing a foundation for future professional knowledge - with the exception of the few with physics specialisation. This is particularly true for the modern chapters of physics, whose task is not so much a specific practical application, as forming attitudes. Lecturers experienced in the methodological issues of physics teaching as well as the modern teaching materials developed by them have a key role in the introductory courses of undergraduate education. Perhaps the most exciting part of the research concerning the teaching of physics is the background work which is comprised of the elementary elaboration of new each territory of modern physics. In the course of this work, the accurate professional knowledge is to be simplified in order to effectively convey the essentials, while the details are integrated into a unified, attitude shaping entity. The inclusion of new, preferably practice-oriented issues in the education is a substantial element, since this may increase the students' interest, motivation for learning and may demonstrate how decisive the role is that physics plays in our everyday lives.

It can be stated that the computer plays a central role in the lives of today's young people, to ignore this fact from an educational point of view is a strategic mistake. What makes it possible to achieve the objectives outlined above are primarily electronic learning materials that arouse interest in the audience, are capable of maintaining their motivation and are suitable for individual (home) processing. It is therefore necessary to create well-thought-out, structured, user-friendly and attention grabbing multimedia learning materials.

Objectives and Applied Methods

In the undergraduate-level education, modern physics is usually represented with a limited number of topics covered (and number of classes). Due to the limitations, the primary goal is shaping attitudes, providing an introduction to the most fundamental concepts and methods of modern physics and demonstrating its most important results. The goal of my PhD thesis is to develop new methods which can be effectively used to explain the topics of modern physics on an elementary level within the limits of feasibility.

My objectives and means of implementation can be summarized as follows:

- presenting the attitude and spirit of modern physics by bringing them into connection with recent scientific results and everyday phenomena, and so arousing the students' interest. Its essence is that, by bringing them in connection with specific problems, I introduce fundamental concepts with elementary discussion, look for opportunities to demonstrate and present the characteristic methods of modern physics in a simple way.
- developing interactive, awareness-raising and friendly e-learning materials to make the physics education more effective through the active participation of the students, which makes the understanding and memorising of knowledge more effective.
- developing a computerised (on-line) test and assessment system to measure the effectiveness of the teaching method based on the above objectives and of the curriculum developed in connection with it.

Theses

1. When teaching the special theory of relativity, mapping phenomena in the Minkowski diagram has a traditional role. However, the quantitative problem solving based on Minkowski-mapping is made significantly difficult by the scale-distortion resulting from the hyperbolic geometry of space-time. I have elaborated a method for simple, quantitative problem-solving based on Minkowski-mapping. I have derived a "scale factor" by reconciling the invariant scalars of the Minkowski geometry and the Euclidean geometry, which makes it possible to determine the distortion of the scale. With this scaling, I have created a Minkowski diagram which allows for reading the solutions with simple parallel projection (using rulers).

From a didactic point of view, this approach to the problems of special relativity has two advantages: on the one hand, it makes understanding special relativity easier, on the other hand, all problems can be solved in two completely different ways (with formulas or plotting), which allows for self-checking, a particularly important aspect of the students' learning process. In order to arouse the students' interest and capture their attention, I have constructed exercises which correspond to their age and reading experiences.

I have proven the didactic effectiveness of the graphical method through statistical analysis with control groups.

2. The analysis of chaotic systems is one of the most important and best-known example of computer-aided experimental physics. The range of chaotic phenomena has an outstanding power to shape attitude with respect to both the teaching of modern physics and the more profound understanding of the results of classical physics. The efficient and modern curriculum to discuss chaos theory is to be based on a user-friendly simulation software, so that the students can preferably experience everything themselves and learn while "playing", in the best sense of the word.

2.A. I have implemented the simulation software, serving to demonstrate the examples discussed during the undergraduate-level teaching of chaos theory, using the programming environment Dynamics Solver, which can be downloaded free of charge. The Dynamics Solver program provides a fully developed and easy to use environment to work with; after downloading and installing, the simulations in the repository can be run directly by simply double-clicking on them. The created repository contains more than thirty simulations.

In my experience, the learning motivation of students is significantly strengthened by experimenting with simulation programs, which they can personally try out and set its parameters.

2.B. The so-called Zeeman's catastrophe machine was originally made for modelling the static behaviour of nonlinear systems. In my thesis, I demonstrate that the dynamical behaviour of the Zeeman machine serves as an extremely valuable example when discussing the properties of chaotic systems. I have demonstrated that the periodically driven machine is an ideal example of a dissipative chaotic system: it can well demonstrate all the essential features and characteristics, moreover such exciting issues can be easily studied with its help as the bifurcation phenomenon, spontaneous symmetry breaking and phase transition. With the machine left alone with appropriate initial conditions, the transient chaos can be demonstrated as well, and by connecting two frictionless Zeeman machines, chaotic motion emerging in conservative systems can be studied.

3. Quantum theory is one of the cornerstones of almost every area of science, today's technology significantly relies on it, yet even its basic knowledge often seems to be the concern of only a small group of physicists and engineers. It is an important task of the modern physics introductory

courses to teach its basic approaches, most essential concepts and methods, as well as its most important applications that determine our present and near future.

3.A. I have worked out a curriculum for teaching the key features of the quantum phenomena. I attempt to bring the spirit of quantum theory closer to the students with the help of the detailed presentation of a specific, really interesting quantum effect, the so-called "interaction-free measurement". I have chosen the representation (a different one from that of the original scientific articles, simplified but correct from a physics point of view) needed for the precise discussion so that it can be understood with an elementary knowledge of mathematics.

3.B. In some academic years, I concurrently taught modern physics and information theory at the faculty of technical informatics of the Kecskemét College. This was when quantum computing, which was regarded as a new discipline at the time, caught my attention and I have included it in the curriculum (among the first in Hungary) on a basic, introductory level.

I elaborated a curriculum in order to create a theoretical summary of quantum computing. I incorporated the use of the "jaQuzzi quantum network simulator" as an important active element of the curriculum, which enables the students to try out the operation of an arbitrary quantum algorithm for themselves. This made learning quantum computing easier and more of an experience.

4.A. The concepts and methods of statistical physics are remote and hard to understand, regarding both their mathematical apparatus and their approach, for the undergraduate-level students participating in the physics courses. It is a significant methodological challenge to discuss these concepts in a way that brings them into connection with interesting everyday phenomena. Gambling, for example, offers a great opportunity to do this, since it is exciting and part of our everyday lives.

I elaborated a curriculum for teaching the basic concepts and approach of statistical physics. Through discussing the famous wheel of fortune, I demonstrate how the instruments of statistical physics appear during operation and in case of correct planning, by identifying the physical quantity of entropy as the hard-to-define but in fact really tangible concept of the game's "excitingness".

An important example of the stochastic processes and the new curricular element generating the most interest from students, is the issue of the Parrando's paradox. Parrondo's paradox is a very recent (about a decade old) finding and it has a very broad interdisciplinary significance. I discuss this topic in detail in the curriculum since, although the consequences and applications of the paradox are well-known in the international literature, they constitute a novelty regarding both the research and education in Hungary.

4.B. As a result of their interdisciplinary nature and wide range of possible applications, complex systems are of particular importance in case of teaching statistical physics. The so-called Zeeman-crystal model, introduced by me, has important features in several respects: on the one hand, it has a real, mechanical basis compared to many other completely heuristic-driven models, therefore it is easier to interpret to the students; on the other hand, it allows for the discussion of every essential feature of the complex systems (e.g. phase transitions, hysteresis, spatial pattern formation, etc.). The crystals form a very wide class of models, which includes the classical (chiral) Potts model as a special case. The actual simulation of the model was realised in the NetLogo environment, which provides a means for the students to get acquainted with and experience computer-aided experimental physics.

5. In the first four theses, content elements are represented from some topics in each field of modern physics (relativity, chaos theory, quantum theory and statistical physics, by order of succession) which are elaborated by me and novel in a certain sense: they either provide a new

approach to the well-known, „conventional" knowledge (e.g. the use of the Minkowski diagram with scale parameters, or the dynamic approach to the Zeeman catastrophe machine, well known as the illustration of the equilibrium behaviour of nonlinear systems, in order to demonstrate chaotic characteristics and simulate complex systems), or the inclusion of some very recent, chronologically new scientific result in the curriculum, in a way well-considered from a didactic point of view (such as Parrondo's paradox or interaction-free measurement).

The subject of this thesis is the interactive computer-aided implementation of the above content elements. I consider the e-learning material I have created and presented in my essay one of the most important practical results of my work. The common essential feature of the created learning materials is their structure, which is developed didactically, promotes autonomic studying, provides the student with a step-by-step guide and is very user-friendly. I intended to achieve the didactic goal by incorporating many types of media content (images, videos, simulations) into each material, with the help of the possibilities of the electronic nature of the program to promote interest, motivation and deep understanding of the students, and by using interactivity.

6. Testing the efficiency of the new professional materials and methods is an essential requirement of the curriculum development work. A lecturer's subjective impressions are not sufficient when judging the effectiveness of the curriculum, the subject knowledge of the students and their competency to apply the knowledge acquired can only be assessed through pedagogical measurements, in the course of which the performance of the students can be estimated with the help of objective, statistical methods. It is a basic requirement that the assessment should be consistent with the curriculum and the teaching methods from both a contents and a statistics point of view.

I have created an electronic check and self-check test-program (with a javascript source) which form an integral part of the applied computerised methods and is complete with (server-side php source) data transfer routine to create a global database accessible online as well. During the creation of the basic version of the program, I considered it an important aspect to be easily adaptable and that users with elementary computer skills can create test programs with optional content and formatting, which can be run in both offline and online mode. The developed electronic test program also proved useful in a nationwide secondary school exam with nearly 400 participants. Based on the statistical analysis, we have come to important and interesting conclusions regarding the energy-related knowledge system of the secondary school students; the results were published.

Conclusions and Applications of the Results

I continuously find applications for the results of my doctoral thesis in my work as a college lecturer. Incorporating the computer into the education offers opportunities in the area of both demonstration (including numerical methods, the use of interactive simulations) and continuous monitoring of knowledge-levels.

Correspondingly, my work covers a large area; from models that can be used in scientific disciplines to the assessment of student competency. In my opinion, it is important to consider the didactics of physics teaching a typically interdisciplinary applied science during this research-development work. Its basis is comprised of the results of the scientific discipline and the directives of pedagogy-psychology constitute their interpretation, while adopting to the age characteristics, interests and competency of the target group. In the present work, the models applied to the Minkowski diagram and the Zeeman machine constitute didactic instruments for which description did not exist before in the scientific discipline. The majority of the electronic learning materials constitute a new solution in their organisation and structure. The computerised test program,

developed for the assessment of the effectiveness of the accomplished teaching materials, meets the requirements for a modern educational assessment. The test program can be used effectively both in the secondary and tertiary education after loading the right content.

I have described my work in national and international journals and demonstrated it at professional conferences. The interest and feedback received during these events indicate that this way of curriculum development can represent progress in science teaching.

During my work, I have elaborated the new e-learning materials regarding both its content and methods in forms ranging from college courses to lectures popularising science. In all cases, I was driven by the promotion of understanding and the maintenance of student motivation; the feedback from my students confirmed it for me that I took the right path and I should continue in this direction.

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