The Feynman Quantum Mechanics with the help of Java applets and physlets in Slovakia

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Quantum mechanics is considered as a theory of difficult and abstract ideas including highly advanced mathematics. At the end of 1970-s R. Feynman delivered a series of public lectures about this theory based on his path integral approach, which have been published in a book: QED - The strange theory of light and matter. This moment is regarded as the important event in teaching quantum mechanics for a wider audience and led to the development of first courses at universities and high schools. We present the Feynman approach with emphasis on the use of Java applets, which help students model a physical situation and come around complicated complex integrals. In addition we present a short review of the project representing Slovakian mutation of Java Physlets originally written by W. Christian and M. Belloni of Davidson College in the US.

I. INTRODUCTION

In 2000 quantum physics celebrated its 100th birthday. Now its importance is not restricted merely to description of certain exotic phenomena, but interferes with daily human experience. The quantum physics theory – quantum mechanics was crucial in understanding radioactivity (leading to nuclear power), accounting for materials such as semiconductors (leading to invention of transistors and integrated circuits used in PC), describing interactions between light and matter (leading to invention of laser) or between radio waves and nuclei (leading to magnetic resonance imaging), predicting antimatter (the important element of positron emission tomography) or discovering wave properties of matter (leading to electron microscopy).

It is a curious historical fact that modern quantum mechanics began with two quite different mathematical formulations. First of them, *the matrix formulation,* originated by Werner Heisenberg in 1925 is very mathematically oriented approach based on matrix algebra. Just about one year later, in 1926, Erwin Schroedinger discovered the wave equation called now Schroedinger's equation that became the cornerstone of *the wavefunction formulation.* Today this formulation represents traditional approach dominating at least last fifty years in teaching introductory quantum mechanics courses.

II. FEYNMAN'S VERSION OF QUANTUM MECHANICS

Approximately fifteen years later, in 1941, Richard Feynman developed a third alternative version of quantum mechanics mathematically equivalent with the previous. The formulation is called *the amplitude formulation* and it is also known as "the sum-over paths theory", "the many paths approach", "space-time approach", "path integral formulation". Feynman's approach rarely presented in textbooks is not well-known among teachers and from the viewpoint of pedagogy it is considered as very "clumsy" in describing simple quantum systems.

However, we recognize two important events in pedagogy of teaching Feynman's formulation that changed the situation dramatically:

1. At the end of 1970-s Feynman prepared and delivered a series of public lectures for non-physicists about quantum mechanics and quantum electrodynamics based on his approach.

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These lectures, which are also in online form (Fig.1) have been published in a small book entitled *QED: The Strange theory of light and matter*[2].

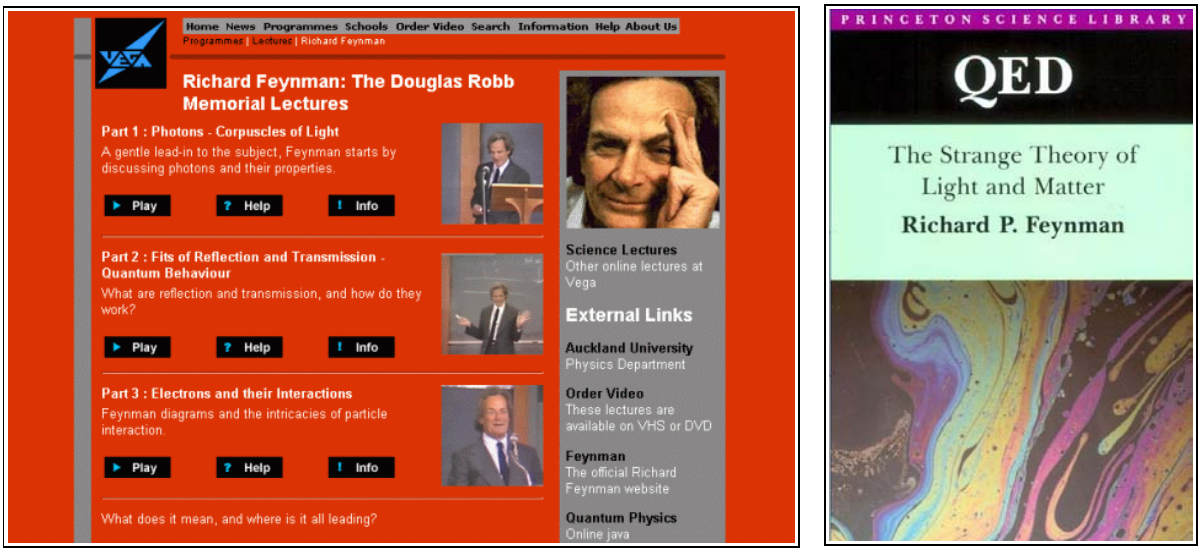

Fig. 1 *The official website* The Vega Science Trust[2] *includes priceless archival recordings of the lectures published in book* QED: The Strange theory of light and matter.

2. The second important event was Edwin Taylor's idea to use an interactive computer software for modeling quantum behavior in terms of Feynman's approach and to apply it not only to photons, but also to nonrelativistic quantum mechanics of electrons.

What are central concepts and ideas of Feynman's quantum mechanics? To give a quick, understandable and eloquent picture of Feynman's approach, we apply it together with definitions in the well-known illustrative example – the photon double-slit experiment.

For explaining the outcome of the photon double-slit experiment we have to know the following three principles:

<u>Fundamental principle.</u> Instead of Schrödinger's differential equation (in case of electrons) or wave equation (in case of photons) the fundamental principle of the microworld in Feynman's formulation is: *Explore all paths!* It means that every particle, e.g. photon, explores each path between source and detector. For example it can go along the double straight line displayed in Fig. 2.

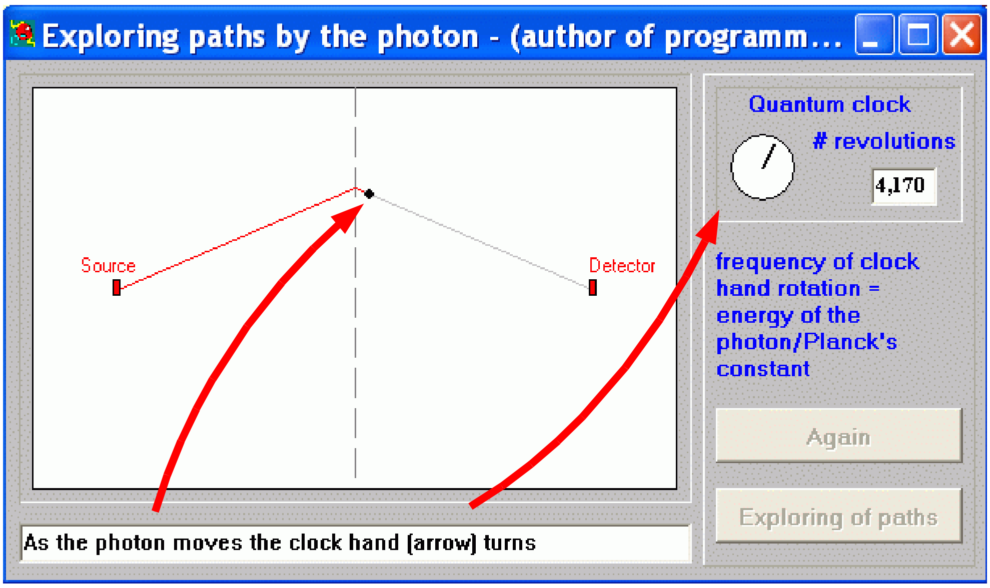

Fig. 2

As the photon moves an imaginary clock hand turns. In other words according to Feynman's formulation for each path of the photon there exists a rotating arrow—a clock hand—called *quantum arrow* .

In case of a photon ("massless particle") with energy E this arrow rotates with the constant frequency given by Einstein's formula $f = E/h$, where h is the Planck constant. Therefore if it takes time t for the photon to go from a source to a detector, then total number of the arrow revolutions equals to $(E\,t/h)$.

In case of electron ("mass particle") the instantaneous frequency of rotating arrow is given by a difference between kinetic and potential energy: $f = (E_k - E_p)/h$. It means that along the whole electron path the total number of revolutions will equal *(average frequency)* times *(time duration)*, or in terms of energies: $[\langle E_k\rangle - \langle E_p\rangle]t/h$. The quantity $[\langle E_k\rangle - \langle E_p\rangle]t$ —*the average kinetic energy* less *the average potential energy* times *time duration of motion*—has a special name in mechanics. It is called *action* and denoted by symbol *S*.

<u>The principle of probability calculation.</u> What is the purpose of the quantum arrow? The meaning and definition of the arrow is represented by the principle of probability calculation: *The outcome of any experiment ("event") cannot, in general, be predicted exactly; only probabilities of the various outcomes can be found. And these probabilities are given by squares of lengths of corresponding arrows called "quantum amplitudes".* It means geometrically a situation in *Fig. 3*.

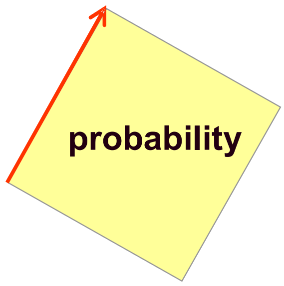

Fig. 3

<u>The principle of superposition.</u> The next central principle of the formulation says: *When an event can occur in several alternative ways, the quantum arrow for the event is the sum of the quantum arrows for each way considered separately.* In the photon double-slit experiment it has the consequences described in (Fig.4).

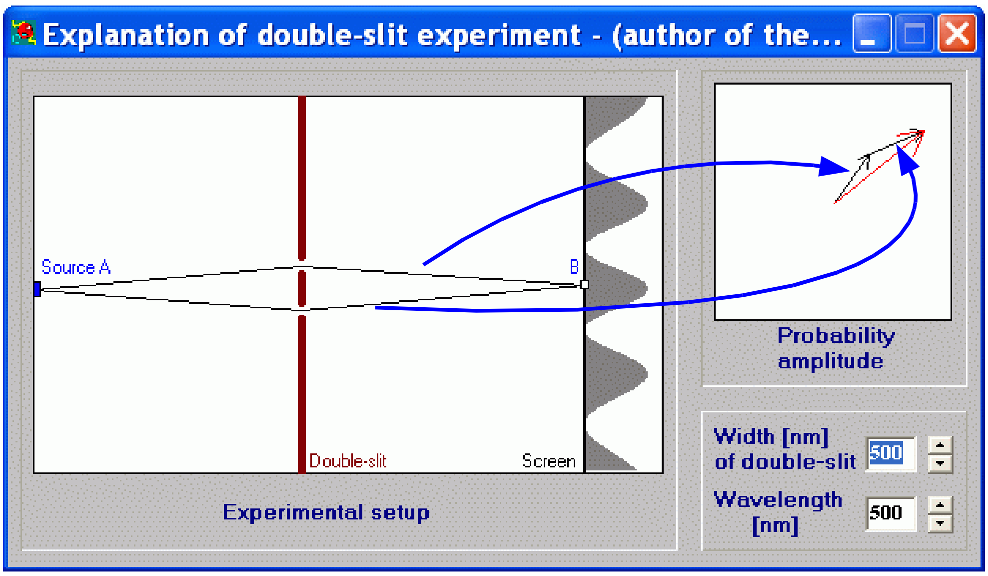

Fig. 4: *The photon has two alternative ways (through two slits) how to get to a given place on the screen. For both ways there exist arrows (black colored) – results of rotating quantum clocks – and according to the principle of superposition the total arrow (red color) for the outcome ("photon hits the screen at the specific place, e.g. B") is the sum of the both mentioned arrows. Finally the square of the red total arrow determines values of probability of the outcome (the gray bar at B). This approach allows us to explore the probability at any place on screen (the gray graph). If we carry out the experiment, we observe the intensity on the screen described by the theoretical prediction shown in the gray graph.*

To be complete we have to mention that there are further important principles (e.g. principle of the sequential factorization or composite factorization) which are not needed in this case, but they are used and explained in detail in other examples (Ref. 2, 4, 5 or 6).

II. CURRENT STATUS IN TEACHING FEYNMAN'S FORMULATION

In this section we present a quick review of the current status in teaching Feynman's quantum mechanics, especially in connection with using computer modeling and software. All notes are accompanied with corresponding references including detailed materials.

Demystifying Quantum Mechanics (1996-2005)

The most pedagogically elaborated work leading to high conceptual understanding, developing intuition and experience is the course of Edwin F. Taylor (MIT, Massachusetts, US) – "Demystifying quantum mechanics"[7]. The course is based on Feynman's QED book and extends the approach to nonrelativistic quantum mechanics.

Edwin F. Taylor

Taylor presents deep ideas of quantum mechanics with:

- only high school mathematics and vector algebra
- no explicit use of complex numbers, no wavefunction formalism, no differential equations

Every step of models assumes students use of computer (Fig.5). The interactive software (2000) written in the platform-independent cT language has a very high pedagogical value and contents. But today this software is rudimentary with not standard and comfortable control. Moreover cT language is no longer supported. For the last ten years the course is taught online[8].

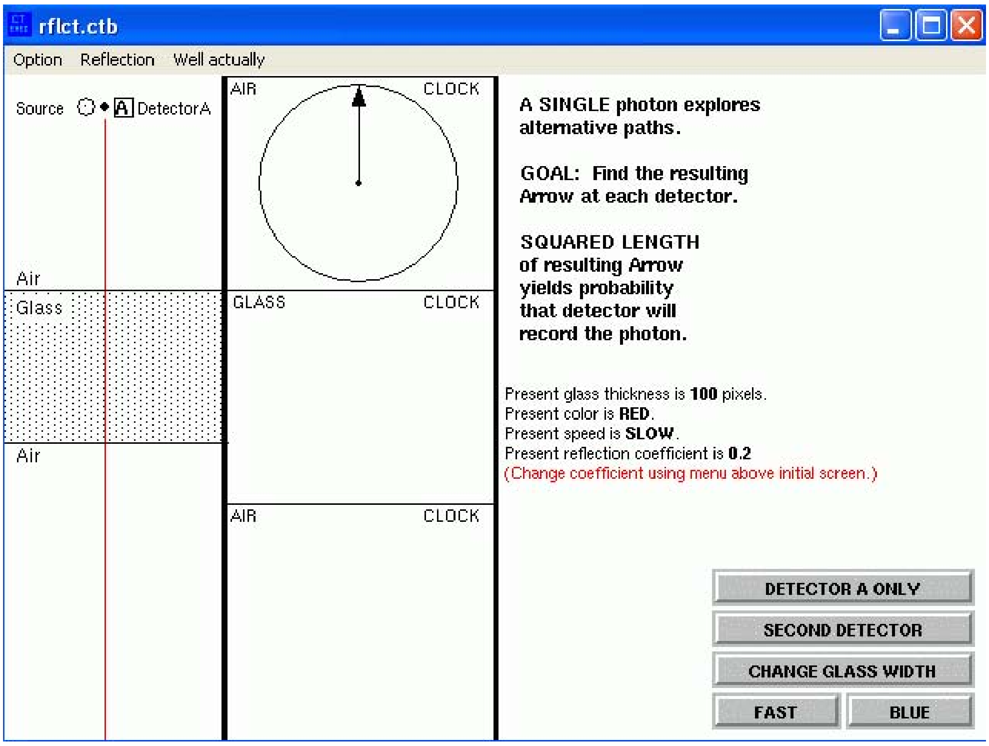

Fig. 5: *A sample of cT program used during exploring partial reflection of light.*

Advancing Physics (2000-2005)

Traditionally basic ideas of quantum mechanics are taken into account only peripherally in teaching physics at our high schools. Main reasons are difficult, abstract ideas and concepts, highly advanced mathematics in this subject, but also unpopularity and its weak understanding by high school teachers.

In 2003-2004 John Ogborn (Institute of Education, University of London, UK) completed directing a large national project "Advancing physics" in the UK that produced a new physics curriculum for the final two years of high school[5]. This post-16 physics course reflects fairly a range of modern activities and trends in physics, as a basis from which students can judge whether to take the subject further. Ideas of Feynman's quantum mechanics became the essential part and represent adaptations of Feynman's QED book and some parts of Taylor's course to high school level in the course .

Jon Ogborn

The integral part of the Advancing Physics curriculum became software MODELLUS (Fig.6) by Vitor Teodoro-Duarte from Lisbon New University in Portugal <http://phoenix.sce.fct.unl.pt/modellus/>.

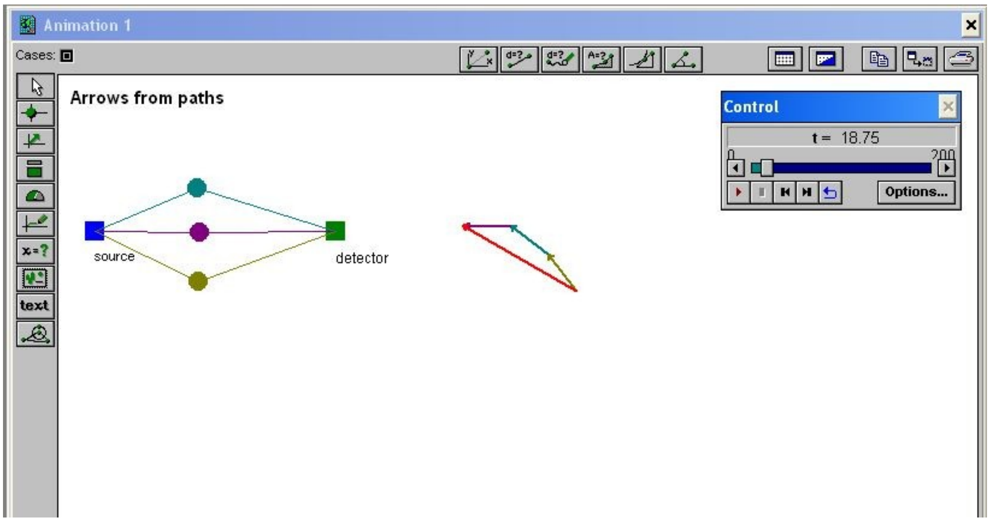

Fig. 6: *Computer display of Modellus in case of modeling quantum behavior of photons*.

<u>The Strange World of Quantum Mechanics (1989-2005)</u>

A course[6] of Dan F. Styer (Oberlin College, Ohio, US) based on Feynman's formulation starts with a simplest quantum system – a spin ½ particle. Unlike Taylor's course it does not consider time evolution of wavefunctions. On the other hand it treats paradoxes like the Einstein-Podolsky-Rosen paradox and its variations and touches modern applications such as quantum computing and cryptography. Lectures of the course were condensed in the book *The Strange World of Quantum Mechanics*[6]**.**

Dan F. Styer

<u>The Quantum World Around Us (1997-2005)</u>

Jim K. Freericks and his colleagues developed a quantum mechanics course[3] for non-science majors—liberal-arts students. The goals for offering the course are to raise the level of scientific literacy of students to a point where they can follow popular-press accounts of scientific discoveries in the areas of chemistry, physics, and materials science and to increase the awareness of students of the impact of quantum physics on their everyday lives. Without advanced mathematics the authors present the fundamentals of quantum mechanics, developed the quantum theory of solids and apply quantum theory to describe materials and devices in our daily lives. Similarly as in previous cases the course is based on Feynman's book and also uses Styer's and Taylor's materials.

Jim K. Freericks

Feynman's quantum mechanics in Slovakia (2001-2005)

We have also developed and tested teaching materials of Feynman's quantum mechanics based on Feynman's QED and Taylor's materials in several courses at high school level (more extended version than Ogborn's) and university level (some new materials in comparison with Taylor's course) with the following syllabi:

Syllabus—University Course (22 hours—each block = two hours at computers)

1. Introduction to the Feynman formulation of quantum mechanics.
   Basic thought experiments—the partial reflection of the light and the double slit experiment.
2. Basic properties of light from the viewpoint of quantum physics.
3. Compound events. Basic principles of Feynman's quantum mechanics.
4. Behavior of the free electron.
   Extra material—Heisenberg principle as a result of Feynman's formulation
5. Principle of least action I (worldlines and their reading, average energies, definition and calculation of the action)[4]
6. Principle of least action II (using action, connections with Newton's laws and conservation laws)
   Extra material—Noether's theorem and symmetries[4].
7. Wave function
8. Propagator and its heuristic derivation
9. Mathematical description of wave functions and propagator
   Extra material—Mathematical apparatus of quantum mechanics—complex numbers (based on Feynman's lectures on physics, Vol. 1 chap. 22-5,22-6)
10. Harmonic oscillator
11. Feynman diagrams
    Extra material—antiparticles as a prediction of the principle of least action

Syllabus—Course for high schools (20 hours - one hour 45 min long)

1.-2. Introduction to Feynman's quantum mechanics (A short fairy tale about Modern physics, A story: Richard Feynman as a colorful character, video and computer simulation of the double slit experiment, questions dealing with modern physics)

3.-4. Fundamental principle: Explore all paths! Partial refelection, calculations of probability, quantum arrow

5.-6. Basic properties of light – reflection from mirror, straigthforward propagation, refraction, difraction

7.-8. Compound events. Calculating quantum arrows. Principles of Quantum mechanics

9.-10. Principle of least action—spacetime diagrams, events, worldlines, reading and drawing graphs, average energy

11.-12. Principle of least action—Definition and calculation of the action, Newton's laws, Conservation laws (How does apple fall?)

13.-14. Quantum-mechanical description of a free electron, transition from quantum to classical mechanics

15.-16. Wave function and propagator

17.-18. Harmonic oscillator

19.-20. Feynman diagrams and positron emission tomography

Besides outlines and teaching materials for students we have developed an interactive software (the extension of Taylor's software) in Delphi (samples in Fig.2, Fig.4), which allows students to do the computer modeling of the fundamental principle, pointing and clicking to tell the electron or photon which paths to explore. However the programs run only on Windows PC. Now we are revising and extending existing materials and preparing a new free-platform software in the form of interactive JAVA applications (Fig.7) in collaboration with Edwin F. Taylor, Jon Ogborn, Mingzhen Tian (Montana State University, Bozeman, US).

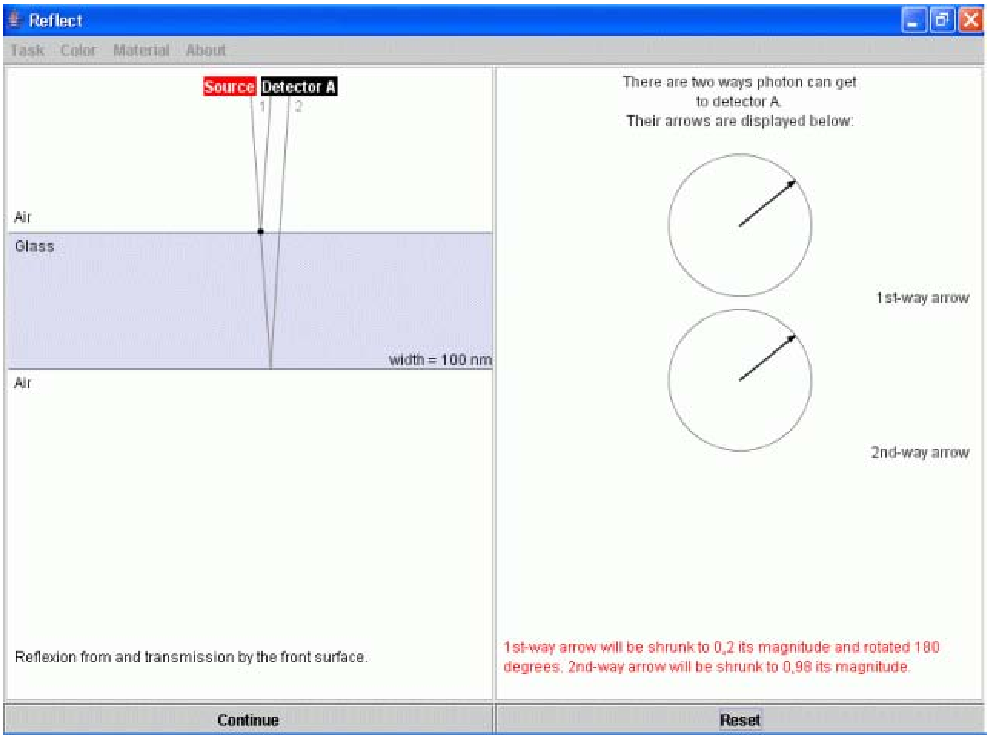

Fig. 7: *A sample of Java application modelling partial reflection of light.*

Concerning the mathematics used, we reinvented and applied Euler's variational method to show that each part of Feynmnan's theory does not go beyond the scope of high school mathematics. Our experience proves that this approach leads to students' enthusiasm, better conceptual understanding of fundamental quantum theory ideas, building intuition and experience, improving ability to work with graphs, increasing creativity. Such approach could be a key to introduction of modern physics in frame of high schools.

Finally the results will be applied in a future Virtual Academy of Young Scientists which should be created at P. J. Safarik University in close future.

IV. PHYSLETS IN SLOVAKIA

We have decided to use the Java technology also in case of classical physics. In 2005 we created a group of Slovakian university and high school educators, which initiated the project – *Physlets in Slovak* – with the aim of preparing Slovak mutation of introductory physics with Physlets[1] (Fig.8) from W. Christian and M. Belloni (Davidson college, US). Physlets, small and flexible JAVA applets, are interactive computer simulations of physical phenomena. Physlets offer active learning experience to students. Designed teaching materials will be offered to Slovak high schools and universities and also used and disseminated through *Virtual collaboration*.

ACKNOWLEDGMENTS

The work was partly supported from the grant of Slovakian cultural and educational agency (KEGA), Project No. 3/3005/05 "Teaching physics by programming models of physical phenomena using inter-active software".

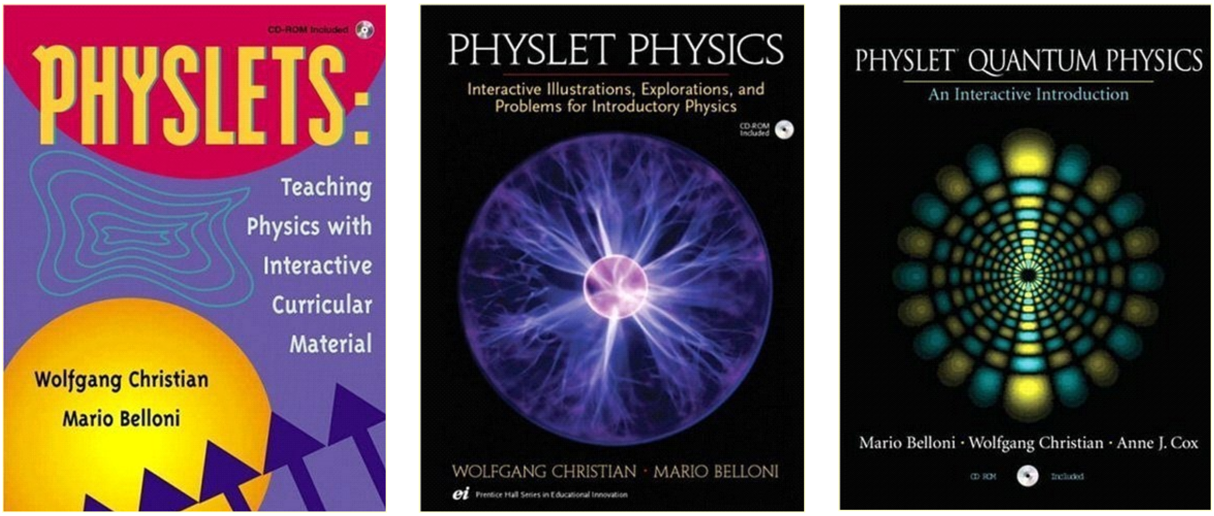

Fig.8

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