Fractal approach to teaching physics and computer modeling
Enfoque del fractal en la enseñanza de la física y modelizacion por computadora

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Abstract

The article presents and appraises the fractal approach to teaching physics using computer modeling in the environment of the object-oriented programming. It manifests the formation of a fractal structure and the corresponding iteration, reflecting the integrity and spontaneity of information perception. The article elaborates the iteration of the fractal structure on the example of studying physics topics, "Geometric optics" and "Wave optics". Each iteration (section of physics) is characterized by a synergy - adding new iteration provides a qualitative perception of the information. The possibility of using this approach in other physics topics and research fields related to physics has been demonstrated.

Key words: *computer modeling, fractal approach, self-organizing processes, synergetic, teaching physics.*

Resumen

El artículo presenta el enfoque de fractales en la enseñanza de la física mediante la modelización informática en el entorno de la programación orientada a objetos. Manifiesta la formación de una estructura fractal y la iteración correspondiente, reflejando la integridad y espontaneidad de la percepción de la información. El artículo elabora la iteración de la estructura fractal en el ejemplo de estudiar secciones de física, «Óptica geométrica» y «Óptica de onda». Cada iteración (sección de física) se caracteriza por una sinergia - la adición de una nueva iteración proporciona una percepción cualitativa de la información. Se ha demostrado la posibilidad de utilizar este enfoque en otras secciones de la física y campos de investigación relacionados con la física.

Palabras clave: *modelización informática, enfoque fractal, procesos autoorganizadores, sinergética, enseñanza de la física*

INTRODUCTION

Innovative teaching of physics and computer modeling of physical phenomena, as well as the application of these methods by teachers, are the focus of special attention in scientific literature (Christian & Esquembre, 2007; Potter & Peck,1989; Sladek, Pawera & Valek, 2011). However, special training of future physics teachers on numerical modeling of physical phenomena, bibliographic data in the pedagogical literature, as well as in educational practice are encountered less often. For example, the curriculum of training future teachers of physics in all five Slovakian universities does not contain this subject. Students and future teachers can get acquainted with the problem of computer modeling of physical phenomena while studying special subjects such as "Digital technologies in teaching physics", "Computer Information Technologies in physics" (http://www.fpv.umb.sk/katedry/katedra-fyziky/studium/bakalarske-studium/). A similar situation with mastering these methods is observed in other universities.

In the process of teaching physics, attention is focused on a significant amount of material and its unstructured character (Özcan, 2015; Hodson, 2014; De Cock, 2012; Fojtík, 2013), insufficient relationship and correlation with other disciplines (Hestenes, 2010; Huffman, 1997) and practical application (Reif & Heller, 1982). It points to the need for information perception in higher educational establishments, especially in teaching physics at an intuitive level, using visualization means, modern advances in programming – object-oriented programming.

The aim of the investigation was the implementation of the educational experiment based on the positive impact of the applied measures aimed at creating the optimal objective of professional competence of future physics teachers. The study objective was to determine the impact of implementing innovative approaches on the willingness and interest of future physics teachers to independently conduct computer simulations of physical phenomena.

METHODOLOGY

There is a relationship between the different branches of physics and among its various sections that can be demonstrated using a fractal approach (Mar'yan & Yurkovych, 2015). This means that in teaching one of the sections (subsections), an algorithm can be determined that is produced and realized in the following sections and, thus, a complex structure is formed while maintaining the integrity of material perception using computer modeling. This approach is tested in teaching electromagnetic phenomena in the sections of physics, "geometrical optics," and "wave optics."

A fractal is a branched or dispersed structure, whose dimension is different from that of an integer (Falconer, 2003). There are geometric, algebraic and stochastic fractals (Frame & Mandelbrot, 2002), applied in various fields of physics in modeling of nonlinear processes, such as turbulent fluid flow, diffusion processes, plasma, porous materials (Shuster, 1984; Haken, 1985). One of the properties of fractals is self-similarity on spatial and temporal scales, which predetermines the usage of one algorithm in the formation of complex structures with a minimum dissipation of energy (Nicolis & Prigogin, 1989; Haken, 2006; Mar'yan & Yurkovych, 2015; Mar'yan & Yurkovych, 2016). This may be illustrated by the so-called Sierpinski carpet in Figure 1. The Sierpinski carpet is a line that has an infinite length and confines a finite area. This line is the self-similar, i.e., composed of three parts that are similar to the entire curve as a whole with the ratio of similarity one to two, and fractal dimension df=1.5849 (Falconer, 2003).

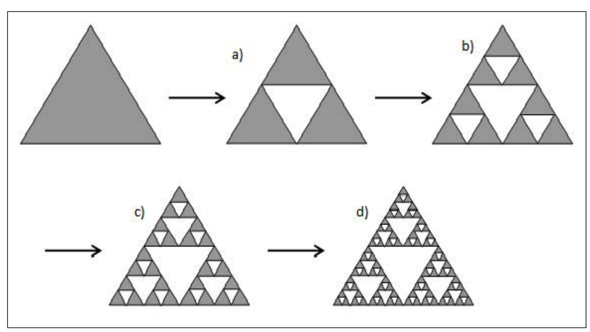

Figure 1: Fractal—the Sierpinski carpet (Falconer, 2003).

It applies the environment of the visual programming, Delphi, and the algorithmic programming language, Object Pascal, which is built on the principles of object-oriented programming and the latest information technologies—RAD (rapid application development), VCL (visual component library), DLL (dynamically linked libraries), OLE (object linking and embedding) (Bucknall, 2001).

The educational experiment involved students of two universities: Uzhgorod National University (Uzhgorod, Ukraine) and the University of Prešov (Prešov, Slovakia). Control groups consisted of 10-18 students. Upon the completion of the students' studies, the test control was conducted, which aimed to find out changes in the knowledge and skills of students after the implementation of the offered approach. A part of the test questions were aimed at ascertaining the interest of students towards the further study of computer modeling of physical phenomena.

RESULTS

Fractal structure. The first iteration.

The laws of reflection and refraction of light (the Law of Snelus). This is analogous to the first iteration of the fractal—the Sierpinski carpet in Figure 1a. The algorithm contains the features of computer modeling of the light propagation process at the interface of two environments, and is further used for the following phenomena (steps), forming a more complex but internally self-sufficient fractal structure.

After consideration of these laws in the environment of visual programming Delphi, the students create the interface (Figure 2): the following components are used (Bucknall, 2001). Students have the opportunity to directly modify the parameters of the optical system (angle of incidence α, refractive index n, the factors of reflectivity and diffuseness), means of visualization of the rays in Delphi environment (colors of the incident and reflected rays, types of lines) and become active self-sufficient participants in conducting computer experiment in Figure 2. It is important to develop the algorithm of information perception by students on the intuitive level that will be used and developed further in later iterations (lectures).

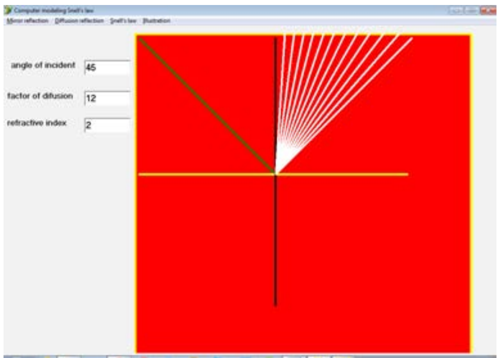

Figure 2: The visual interface of modeling the laws of light reflection and refraction in the Delphi environment.

The second iteration.

Total internal light reflection in Figure 3. This is analogous to the second iteration of the fractal—the Sierpinski carpet in Figure 1b. It is important to note that the formation of this and subsequent iterations retain the "algorithm" of the fractal structure incorporated for the previous iteration that ensures the integrity, self-sufficiency and localization of perception. It is important to use computer modeling (Gould & Tobochnik, 1988), which determines the cross-cutting nature and the spontaneity of the material presentation, the features of object-oriented programming languages developed on the principles of encapsulation, inheritance and polymorphism (Bucknall, 2001; Cantu, 2008). Because of this, each iteration makes use of the properties of the previous one, and, at the same time, it must contain new information (property, method)—in this case, the possibility of directional light propagation.

The illustration of the refraction laws and total internal reflection in Delphi environment are depicted in Figure 3. Students get the opportunity to change the parameters of the optical environments, to observe the ray propagation in real time under total internal reflection.

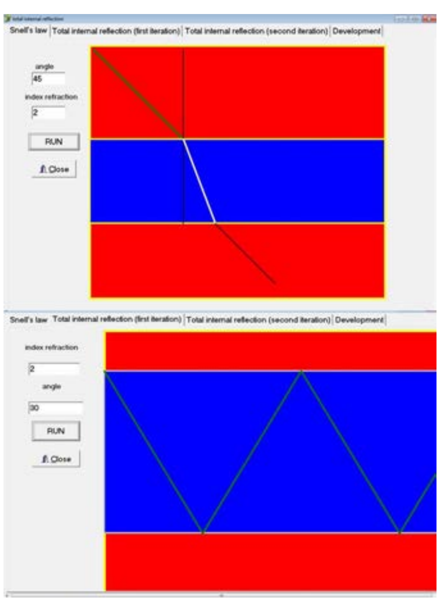

Figure 3: The visual interface of computer modeling of the total internal reflection phenomenon.

The third iteration.

Determination of light transmittance of a thin film taking into account multiple reflections and using the methods of approximation in Figure 4. It is analogous to the third iteration in Figure 1c.

Students are introduced to the concept of light absorption - the phenomenon of the reduction of light wave energy during its propagation in the substance as a result of converting wave energy into other forms of energy. To experimentally obtain dependences of transmittance upon the wavelength in the visible region of the spectrum, the students carried out the two-parametric approximation method (Hestenes, 2010). The two-parametric dependence has been considered: $y=ge^{mz}$, where m,g variational parameters which are determined in the process of computer modeling (Figure 4). The visual interface of the calculation program in Delphi environment is given in Figure 4. The qualitative difference of this iteration consists of introducing the analytical dependence and its graphical visualization. However, there remains the need inherent in previous iterations of structuring teaching material and enhancing students ' attention, involving them in the formation of the fractal structure (Mar'yan & Yurkovych, 2015).

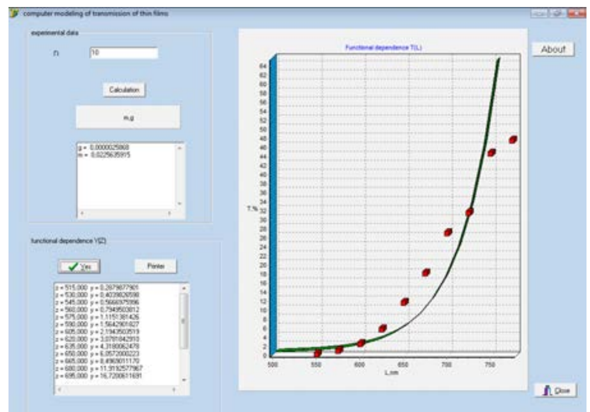

Figure 4: Visual interface of two parametric approximation of light transmittance in the Delphi environment.

The fourth iteration.

Modeling of the optical characteristics of the positive and negative lenses in Figure 5 is analogous to the fourth iteration in Figure 1d. In order to perform the fourth iteration of the fractal structure the students have been familiarized with some methods of determining the focal distances of converging lenses taking into account the position of the principal planes and the refractive index of the lens material.

The optical power of a thick lens can be calculated by the formula:

$$\Phi = \frac{1}{f'} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) + \frac{d(n-1)^2}{n \cdot R_1 R_2}$$

where f ' – the back focal distance of the lens, R_1 and R_2 – the radii of the refractive surfaces curvature, n - the refractive index of the lens material, d - the thickness of the lens.

In the process of using computer modeling (Gould & Tobochnik, 1988) there exists a significant contribution of graphical tools for data visualization (building various types of graphs for a single analytical dependence, that is, one and the same analytical dependence is observed by students at different visual foci) in Figure 5.

The fifth iteration.

Practical application of the given physical phenomena in Figure 6. It should be noted that the fractal structure has a fractional dimension, completely filling in the corresponding space (Mar'yan & Yurkovych, 2015). The practical application itself is analogous to the fifth iteration in Figure 1 and reproduces the integrity and development of the section of physics, "geometric optics." (Mar'yan, Kikineshy & Mishak, 1993; Mar'yan, Kurik, Kikineshy, Watson & Szasz, 1999; Young & Freedman, 2003).

To create the interface of the program in Figure 6, students were asked to use the object Image in Delphi environment. The students got acquainted with the technical product — optical fiber consisting of an optical fiber waveguide, protective coatings and marking colored membrane.

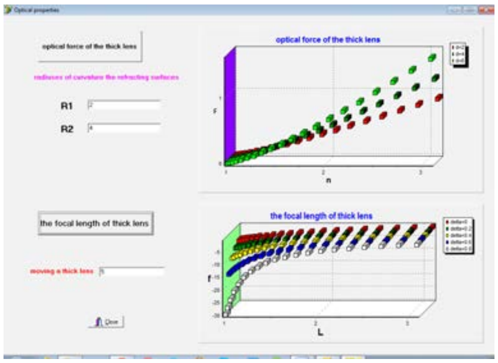

Figure 5: The visual interface of modeling optical parameters (optical power and focal distance) of a thick lens.

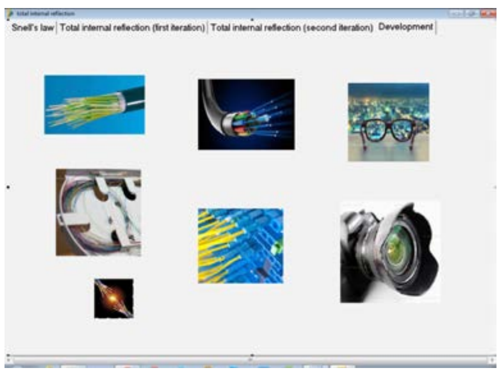

Figure 6: Practical use of the phenomenon of total internal reflection in fiber-optic communication lines and optical lenses.

Each iteration (section of physics) is characterized by a synergy - adding a new iteration provides a qualitative perception of the information (without an additional introduction of the division according to themes). This encourages the student to become an active participant (Haken, 2006; Mar'yan & Yurkovych, 2015). This synergy creates a unique fractal structure, capable of development and functioning (Mar'yan & Yurkovych, 2016).

The iteration discussed above can be complemented and developed, in particular by involvement of learning using the testing tools (Hodson, 2014), with the exchange of information using the Internet (De Cock, 2012), that is, the process generates and allows an infinite number of steps, which is essential for fractal structures (Frame & Mandelbrot, 2002).

Based on the presented approach of the joint synergistic usage of lectures on physics and computer modeling, the fractal structure (table 1) is formed on an intuitive level (Sherin, 2006). Functioning of this structure is manifested in the transition to students' self-sufficiency, involving the use of a creative approach and the desire to apply the obtained information in radically new areas (Young & Freedman, 2003). For example, the phenomenon of total internal reflection along with the classical perception of physics as a process of dissemination of information (informatics). Or, preparing a hamburger (cooking) as related to the Belousov-Zhabotinsky reaction with the formation of dissipative structures (chemistry), dancing rhythms (music).

Table 1. The formation of the fractal structure of information perception.

Steps	Levels of information perception
The first step	Physics
The second step	Physics and computer modeling
The third step	The intuitive perception of information by students and the formation of the fractal structure

The resulting fractal structure is qualitatively manifested in the table 2.

Table 2. Fractal structure in the study of physics sections "Geometric optics", "Wave optics".

Iterations	Objects
The first iteration	Computer modeling the laws of light reflection and refraction
The second iteration	Computer modeling the laws of light reflection and the total internal reflection phenomenon = { Synergy of integration in the Delphi environment }
The third iteration	Computer modeling the laws of light reflection, the total internal reflection phenomenon and two parametric approximation of light transmittance = { Synergy of integration in the Delphi environment }
The fourth iteration	Computer modeling the laws of light reflection, the total internal reflection phenomenon, two parametric approximation of light transmittance and the modeling optical parameters of a thick lens = {Synergy of integration in the Delphi environment }
The fifth iteration	Computer modeling the laws of light reflection, the total internal reflection phenomenon, two parametric approximation of light transmittance, the modeling optical parameters of a thick lens and practical use of the phenomenon of total internal reflection in fiber-optic communication lines and optical lenses ={Synergy of integration in the Delphi environment}

DISCUSSION

Thus, a fractal structure in teaching one of the sections of physics, "geometrical optics," is formed (it can be easily spread to other branches of physics). The advantages of this approach are obvious: the corresponding physics section is perceived as a single unit without the mechanical separation into its component parts; and the possibility of forming branched structures according to a single algorithm that can be extended to other branches of physics, while maintaining the integrity (fractality) at the level of several sections (Breslyn & Mcginnis, 2012; Kuo, Hull, Gupta & Elby, 2013). The given approach is also used in the formation of a fractal structure, which is implemented, in particular, in the transition from geometrical to wave optics. Moreover, the iterations analyzed above, iterations 1–5 in Figure 2–6, are considered as the first iteration of a new fractal structure formation. It should be noted that unlike the classical approach, which is based on the assimilation of a certain amount of material (Özcan, 2015; Hodson, 2014), the fractal connections reflect the internal structure of the sections (Mar'yan & Yurkovych, 2015; Mar'yan & Yurkovych, 2016) that are assigned spontaneously. In computer modeling, along with the use of the algorithmic programming language, Object Pascal, other object-oriented languages such as C++, Java, and Ruby, can be used.

The offered fractal approach was tested in Uzhgorod National University (Ukraine) for students at the Faculty of Physics and the University of Prešov (Slovakia) for students of humanities and natural sciences at the Department of Physics, Mathematics and Technology. Unlike Slovakian universities which train physics teachers, Uzhgorod University has considerable experience in applying computer modeling of physical phenomena.

The study carried out the evaluation of the quality of training of the discipline "Programming and mathematical modeling" for students of physical faculty according to the specialization "physics teacher" (a group of students consisting of 16-18 people) in Uzhgorod National University during the period 2012/2013-2015/2016. Figure 7 manifests the diagram showing the dependence of the assessment rating for 2015/2016 academic year in the process of teaching material during 12 lessons (lessons included lectures and laboratory classes). We observe the growth of students' academic performance in mastering the discipline (assessment ratings are in the range of 82-89 B, 90-100 A), which is confirmed by the diagram in Figure 7. Students' activation point and deeper perception of the material are realized in the range of the 2nd-4th lessons (Figure 7, profound knowledge is gained 82-89, excellent marks are formed 90-100 A). Similar results were obtained for groups of students of this specialization, who studied in 2012 / 2013-2015 / 2016 (Figure 8 represents reduced ratings of the final assessment (final lesson 12, Figure 7)). That is, the obtained dependence in Figure 7 is not accidental; it is naturally manifested owing to the fractal approach of teaching physics processes during 4 years (Figure 8).

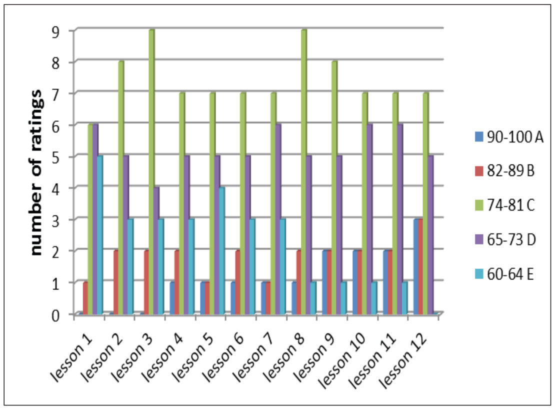

Figure 7: The diagram of the dependence of assessment ratings in 2015/2016 academic year

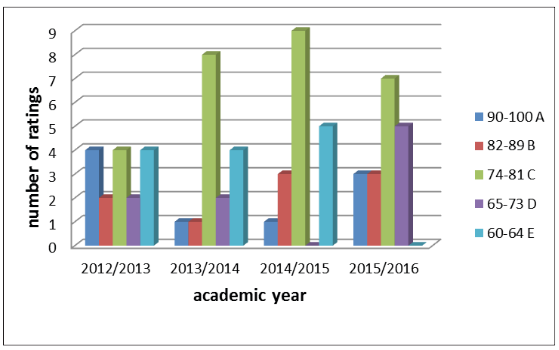

Figure 8: The diagram of academic performance in the study discipline "Programming and mathematical modeling" for 2012 / 2013-2015 / 2016 academic years

The research in Prešov University was conducted in 2015-2016 academic year. The experiment involved 10 students in the study subject "Methods of teaching physics" including computer modeling of physics sections "Geometrical optics", "Wave optics". The conducted rating control indicates the students' interest in computer simulation used in teaching physics in 93% of future physics teachers and the increase in their level of mastering material by 11%.

During these classes, the activation of students, and in-depth perception of the material have been noted. In our opinion, the adoption and usage of the methodological approach of modeling physical phenomena and processes by future teachers of physics is very useful (Windschitl, 2004). It creates space for the expansion and implementation of the key competencies in the area of targeted and effective use of information and communications technology in school physics experiments (Luft, 2001; Lotter, Harwood, & Bonner, 2007; Schwartz, & Lederman, 2008).

CONCLUSIONS

The fractal approach to teaching physics using computer modeling in object-oriented programming, Delphi, has been substantiated. The formation of a fractal structure has been established and the iteration has been determined, which reflect the integrity and spontaneity of presenting information. The application of fractal approach for students of the Physics Faculty in Uzhgorod National University in 2012 / 2013-2015 / 2016 academic years shows the increase in the level of academic performance by 28-30% (the increase in the number of students who received grades in the intervals of 82-89 B, 90-100 A) and the decrease by 30-34% in the number of students who received grades in the range of 60-64 E, 65-73 D.

The lectures for students of Prešov University in Slovakia with the use of a fractal approach in teaching physics sections "Geometric optics", "Wave optics", and computer modeling have been conducted. The rating control of interest level to teaching computer modeling for future physics teachers comprises 93%, and the academic performance has increased by 11%. The involvement of students of related majors in two universities - Uzhhorod and Prešov - demonstrates the feasibility of using fractal approach in preparing future teachers of physics in higher educational establishments.

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