Investigating the spread of pollution in secondary school: Exploratory learning of nonlinear and chaotic features

PhD Theses

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Introduction

Although the phenomenon of chaos has been familiar in everyday language for almost 40 years, the potential that can arise in science and physics education in relation to the subject is still far from being exploited.

Chaotic phenomena are a completely new form of motion. It is almost unbelievable how many fields we encounter them in, the variety they bring, and this is what gives them their beauty. It is also surprising that chaos is not the exception, but rather typical. Chaotic behaviour extends to the problems of weather, pollution and even climate change. With all this in consideration, it makes sense to teach chaotic phenomena in secondary school.

It is also important to give students a taste of a field of modern physics which, as well as being found in many areas of science, is on a macroscopic scale, making it more accessible and palpable than traditional modern physics.

A surprising consequence of the chaos phenomenon is that sensitivity to initial conditions is often found in simple systems, systems whose motion is completely determined by a few equations. Chaos physics can be introduced to secondary school students through these simple systems.

Objectives

My aim was to present the phenomenon of chaos not through videos made by others, running prefabricated simulations or a lot of mathematical reasoning, but through experiments carried out by the students and activities that interested them. I have also been careful not to distract them from distant and not necessarily proven, but sound interdisciplinary aspects (e.g. brain activity, earthquakes, stock market dynamics). My teaching practice is therefore mainly limited to physics and environmental physics, highlighting the wide occurrence of the chaos phenomenon in the co-disciplines.

Experiments are also of primary importance in learning about chaos. In my own experience, experiments carried out by students have played the most important role. The use of digital tools is also inevitable for the evaluation of measured data.

As a teacher I realised that the nature of chaos can be effectively explored through handicraft: the technique of marbling - mixing paints on the surface of water and then fixing them on paper - is an effective way to explore the characteristics of chaotic drift that describe the mixing of materials in a medium. At the same time, it engages students very well, immersing them in the creation, in parallel with the discovery of the nature of the phenomenon. It motivates them to explore the subject, and where appropriate, to learn more deeply. This is a new direction in international literature.

It was also a surprise to me that a recent application, RePLaT-Chaos-edu, offers almost the same opportunity to teach chaos using the example of the spread of volcanic ash, a problem linked to environmental pollution, which also reinforces students' environmental awareness.

Both accessible ways of understanding chaos: through the technique of marbling and through the study of the spreading of volcanic ash, are worthy of widespread introduction in Hungarian physics education.

In addition to the limited classroom space, the project framework provides an excellent opportunity to develop the topic and to delve deeper into chaotic phenomena, the exploration of which is also one of my goals.

Theses

1. **Chaos experiments in secondary school physics education** [1, 2]

I have shown that simple physics experiments, mainly in mechanics, can help secondary school students understand the essence of chaos.

Simple, playful experiments are a good way to raise interest in chaotic phenomena and to study the characteristics of chaos. Examples include the magnetic pendulum, the double pendulum, and the double-slope bouncing ball. Based on my experience, pupils are able to record and independently analyse the data from the experiments they have carried out.

The pupils have experienced that the simple chaotic systems they are investigating are unpredictable, even though the equations of motion of these systems are known, i.e. the motion can be described using Newtonian mechanics. Through these experiments, students themselves discover that simple systems can exhibit complex behaviour. In my experience, secondary school students easily understand the experimental aspects of chaos. Through experimentation, they experience the joy of discovery and the thrill of exploration.

2. **Study of nonlinear systems using digital methods** [2]

I have demonstrated that studying simple chaotic mechanical systems with digital tools can be done in high school. The characteristics of chaos are successfully studied by students, and sensitivity to initial conditions is recognized.

Experiments with simple chaotic systems are recorded by students using a mobile phone or a camera. The motions, such as a ball bouncing on a double slope, are analysed using the video analysis software Tracker, which in my experience is the right software for the job.

There are many ways of comparing two motions with a close initial condition. In the physics lesson, this was done by means of an experiment presented by the teacher. The students themselves carried out the experiments in a workshop or as part of a project.

They used Excel worksheets to analyse the movements graphically. In my experience, Excel is suitable for this purpose, its graphs clearly show the sensitivity to initial conditions, i.e. the widely used term "the butterfly effect", and its magnitude can be determined.

3. **Crafts in chaos teaching** [3, 4]

I have developed and implemented good practices for learning about chaos physics through craft activities such as marbling.

Handicrafts, and more specifically the marbling technique, have proven to be a very effective tool for learning about chaotic processes, as the mixing of paints on a liquid surface is a chaotic process. Chaotic drifting was studied in marbling, i.e. mixing paints on the surface of water and fixing the patterns on paper or other substrate (candles, eggshells). During the process, the students observed how the patterns were formed as the paints were mixed. They recognised the characteristic shapes seen in the phase space during the chaotic process. They learnt about the basic characteristics of chaos: stretching and folding back. The rapid elongation of the initially concentrated paint droplet illustrates the sudden separation of trajectories, the sensitivity to initial conditions, observable to the naked eye.

I have found that the joy of creating and the aesthetic experience can stimulate interest in the subject, while helping students to understand and deepen their knowledge. Pupils experience a state of flow, a state of reflection, enthusiasm and attentiveness. This activity engaged the children so much that we invited the parents to join us in creating - painting eggs - and sharing their knowledge.

4. **Inquiry-based learning in secondary school science based on volcanic ash spreading** [3, 4]

I have shown that the RePLaT-Chaos-edu application is a successful, effective experimental tool for students to investigate the spread of environmental pollution and learn about the characteristics of chaos.

The RePLaT-Chaos-edu application was developed for secondary school students to monitor the atmospheric spread of ash clouds following volcanic eruptions. The application simulates the atmospheric dispersion of dust clouds emitted at a user-selected geographic location and altitude using measured wind speeds.

The use of RePLaT-Chaos-edu is an opportunity for inquiry-based learning: I will show how it was discovered and formulated independently, through play, that the spread of pollution clouds is not patchy but has a filamentary structure. They discovered the characteristic effects of predominant winds and cyclones also.

I have shown that an important characteristic of chaos, such as the "butterfly effect", can be easily quantified by the elongation rate, which can be easily measured by students using the application's dedicated module.

The application helps to raise students' awareness of the importance of chaos in environmental phenomena. In my experience, RePLaT-Chaos-edu has proved to be a complete success: an effective experimental tool for studying the atmospheric dispersion of pollutants and the characteristics of chaos.

5. **Students' feedback on the use of the RePLaT-Chaos-edu volcanic pollution spreading simulation** [3]

I investigated students' experiences in individually mapping and using the RePLaT-Chaos-edu, an application simulating the atmospheric spreading of pollutant clouds. Based on questionnaire responses, I found that the majority of students found RePLaT-Chaos-edu interesting and useful.

The students used the application simulating the spread of volcanic pollution with great enthusiasm, enjoying the joy of discovery and getting into a state of flow. My aim was to find out how interesting and useful the students thought the application was. I also conducted a questionnaire and an open response survey, the results of which I processed graphically. Based on my survey, the majority of students found the application interesting and useful, and experienced it as a discovery. No student answered that it was not interesting to work with the programme.

The students discovered that the application helps to develop environmental awareness and can also be used in the context of geography education. Among other things, the application helps them to understand an important feature of the large-scale, global atmosphere: the students have recognised that volcanic ash only spreads in one hemisphere within the time frame provided by the application.

6. **The aesthetics of chaos, patterns on different scales** [3, 4]

I showed that students can recognise patterns of chaos at different scales, and in different processes, and see the similarities between them.

The environmental phenomena show structures similar to the patterns formed during marbling. The students had the opportunity to compare the patterns formed during the mixing of paints with photographs of the spread of environmental contaminants, such as oil spills on the surface of water, and finally volcanic ash spreading through the atmosphere. In my experience, the similarity between patterns formed in different ways and at different scales has been recognised, and this universality has had the power of discovery: chaos leads to the emergence of similar patterns at all scales.

In my experience, this topic is also very suitable for completing festive physics lessons (Christmas, Easter, Children's Day). In the context of aesthetic impact, I feel it is inevitable to introduce students to the concept of fractals. In addition to the mathematical aspects and examples, it is worth emphasising the Cantor heap, since the fractals that appear in the mixing process are all deformed Cantor strands, and thus such patterns are also formed during marbling and chaotic drifting. It is this mathematical structure that is behind the universal occurrence.

7. **Projects**

I have shown that it is possible to successfully raise students' awareness of the importance of chaos not only in class, but also through project work in secondary school.

As class time is limited, many topics can be explored in depth through project work. I have developed project plans and conducted project activities on the topics of chaos physics and atmospheric pollution dispersion. I showed that in a week-long project, secondary school students can become familiar with the characteristics of chaos.

The themes for the week-long projects were: Chaos physics: digital and craft; Art and physics: chaos physics; Chaos physics: environmental physics. The projects were carried out within the framework of the traditional project weeks of Szent István High School.

For the project Art and Physics: chaos Physics, I prepared a note booklet for all our students, which helped us to achieve the project's objectives.

Summary, goals and further plans

I think it's important to introduce the concept of chaos to the public, to explain the difference between the everyday and the scientific term.

In the right structure of chaos teaching, we come closer to understanding and appreciating the nature of environmental flows. I consider it essential to raise awareness of the chaotic nature of the spread of environmental pollution. By understanding the characteristics of chaos, we can become aware that the consequences of environmental pollution are not only local, but also on a larger scale.

In the future, I would like to continue to present chaos physics in classes, workshops and projects. A promising direction seems to be the investigation of so-called plume diagrams, which can be obtained by parallel tracking of movements from several close initial conditions. The separation of the diagrams clearly indicates unpredictability, regardless of detailed knowledge of the system. This can be demonstrated experimentally at secondary school level.

I plan to carry out and evaluate simple mechanical experiments with my students. I would like to harness the power of the joy of creation, the aesthetic experience, the state of flow, both in arousing interest and motivation, and in persistent experimentation. I plan to continue to report my research and results to my fellow teachers at conferences and workshops, and to share my experiences, good practices and results with interested teacher candidates.

Publications related to theses

1. I. Bajkó: *Chaos Physics in Secondary School – A Material Applicable in Online Teaching* Horizons of mathematics, physics and computer sciences **50**, 22-34 2021

2. I. Bajkó *Chaos Physics in High School - Challenges in Multimedia Application* GIREP Conference 2022 J. Phys.: Conf. Ser. 2297 012006

3. I. Bajkó: *Inquiry-based Science Teaching – The Use of RePLaT-Chaos Application*, proceedings of TIM Conference 2022, accepted for publication

4. Bajkó I.: *Felfedező tanulás a középiskolai természettudományokban a vulkáni hamu terjedése alapján,* Fizikai Szemle 2022/9 pp. 291-296.

Presentations related to the theses

I. *Chaos Physics in High School - Challenges in Multimedia Application* GIREP Conference Malta, 16-18. November 2020

II. *Inquiry-based Science Teaching – The Use of RePLaT-Chaos Application* TIM Conference, Temesvár 11-13. November 2021

III. *Káoszfizika tanítása középiskolában – felfedező tanulás,* Physics Teachers' Transylvanian Conference, Jósikafalva 14-16. October 2022