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Chaos Physics in High School – Challenges in Multimedia Application

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Abstract. Besides being an active field of research, chaotic phenomena are also encountered in our everyday life, thus it's worth discussing them also in formal education in public schools. This paper presents the authors' experiences in teaching chaos on secondary level. A teaching module that encompasses mechanics lab experiments and numerical simulations of typical chaotic systems have been implemented and evaluated. The module offers a number of multimedia applications whose availability in teacher education is also discussed.

1.Introduction

Chaotic processes can be experienced in almost every branch of science. The scientific literature on chaos theory encompasses large review books that swipe over several chaotic examples [1], [2], [3], [4]. From the wide diversity of chaotic systems, we selected some simple mechanical examples from the introductory textbook [3], and the associated e-learning materials [5] that allow treatment on secondary level. In the last couple of years, we offered a chaos module to students in penultimate or last year of high-school [6]. Most teaching activity took place in study groups in extracurricular framework.

At the beginning, we allowed students to discover chaotic phenomenon by carrying out experiments on their own with simple physical systems (magnetic pendulum, driven pendulum, elastic pendulum, and ball bouncing on double slope) that exhibit chaotic behaviour. The very important take-home message from this part of the course was that even simple systems can behave in an unexpected way. Through experiments and associated computer simulations students became acquainted with three important characteristics of chaos [3], namely (i) irregularity of the motion, (ii) unpredictability, i.e. sensitivity to initial conditions, and (iii) order in the form of specific geometric patterns, i.e. the fractal structures that appear in the phase space.

Since chaos is typically the field whose hidden face can be unveiled most efficiently with digital tools, we used a number of multimedia applications in the teaching process. In the terminology of [7], our main contributions are thus in digital technology, in the method of research (enquiry based learning), and in modelling. The main aim of the present publication is to give a brief overview of the digital resources we found most useful in teaching chaos. Since in the past few years physics education has started to include more and more approaches based on digital technologies, our list of free and easily accessible digital tools might also be useful in teaching physics and science subjects in general.

The paper is organized as follows. In the next section we review how digital technologies can improve chaos-teaching. First, I present a Tracker-mediated measurement performed by students in the case of a ball bouncing between two slopes. Next, I show how Excel worksheets can be used by students to visualize the butterfly effect, which is essentially the sensitivity of the outcome to the initial conditions. Since modelling is also essential for a deeper study of chaos, finally in the next section I focus on a platform that allows numerical simulations (associated with Excel) without previous programming skills. In section 3, we describe what kind of competencies physics teachers need in order to teach chaos physics efficiently using ICT. Here the current situation in teacher-training in Hungary presented. Section 4 is devoted to the introduction of complete multimedia material which supports the understanding of the main characteristics of chaotic systems, such as an e-learning page exhibiting different facets of the butterfly effect (4.1), and a gamified approach (4.2). In this latter framework, we use a program which simulates the spreading of volcanic contamination in the atmosphere. In the last section I summarize our conclusions.

The learning path of the teaching module is as follows: (1) carrying out experiments by the students, (2) data assimilation and handling which lead to the discovery of the butterfly effect, (3) numerical simulations on three levels (teacher presented simulations, those carried out by the students relying on the Excel-based e-learning material offered and the use of Dynamics Solver), (4) running ready-made programs, e.g. RePLaT- chaos. Optionally the module can be expanded by (5) craft occupation with the marbling technique, involving the mixing of paints on water, mentioned at the end of section 4.

2. How can digital technologies improve chaos-teaching?

2.1. Tracker-mediated measurements

Chaos-related measurements cannot be evaluated properly without software that converts observations into data. I found that the Tracker video analysis and modelling tool is quite adequate for this purpose. In the chaos teaching module, we employed this software to track the position of a ball that bounced between two slopes facing each other (Figure 1.) - a simple mechanical experiment known to exhibit chaotic behaviour.

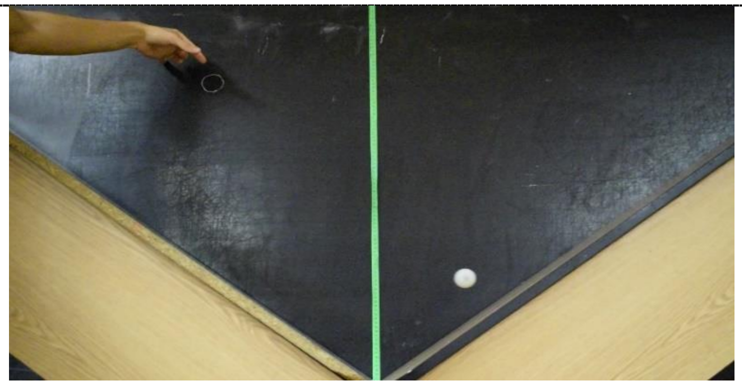

Figure 1. Ball bouncing on a double slope (picture taken by the author)

I asked the students to video-record different motions of the ball that start nearly identically and track the position of the ball as a function of time in each case with the Tracker program. In Figure 2, we can see one of the outcomes.

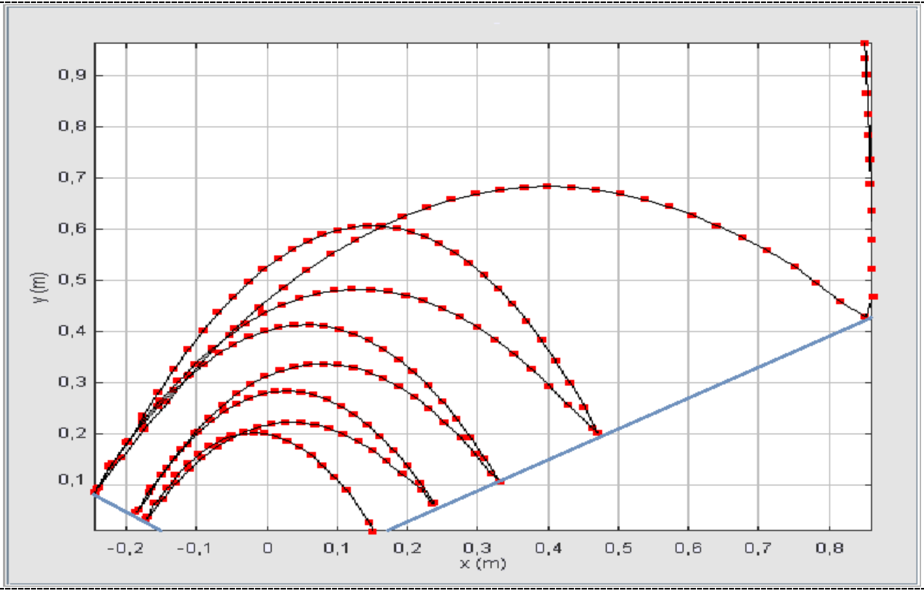

Figure 2. Trajectory of the ball bouncing between two slopes, digitalized by the students with Tracker (the ball was released at x = 0,9 m, y=0,95 m).The distance between the point of bounce and the line representing the slope provides a hint on the accuracy of the measurement.

Subsequently, we used the Microsoft Excel software to visualize graphically pairs of time series (trajectories) that started from nearly identical initial conditions. The picture made immediately clear that the two plotted paths are rather different (see Figure 3.). Thus, the students were able to witness the butterfly effect in their own experiment. They could see that imperceptibly small inaccuracies in the initial condition could lead to grossly different scenarios. The study demonstrated beautifully the sensitivity to initial conditions.

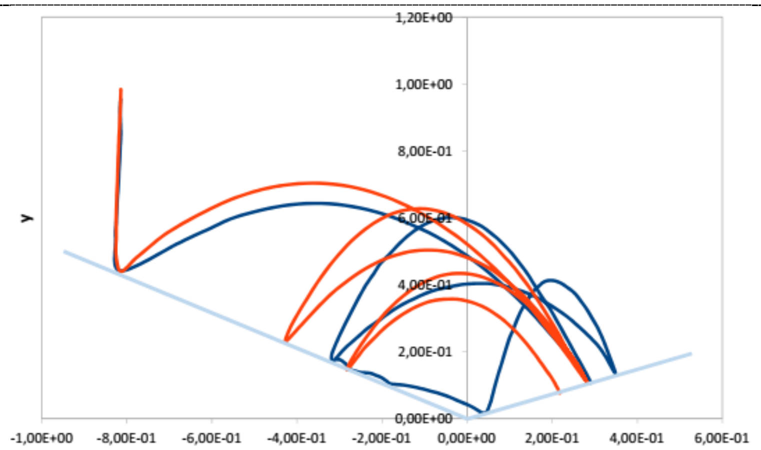

Figure 3. Comparison of two time series starting from nearly identical initial conditions in Excel.

Notice that even though the two plotted trajectories started from nearly identical positions, in one of the cases (red line) the ball bounces on the right slope in the last minute of our observation, while in the other case (blue line) it bounces on the left slope, so the two lines end up on opposite slopes after the same amount of time.

2.2. Excel-based simulations

In chaos education it is also important to engage students in modelling and computer simulations. For their first steps in modelling, students can use their Excel platforms again, together with the freely available, Excel-based e-learning material on webpage [8]. This e-material is very well structured. After an interactive introduction that helps students solve equations of motion numerically, it offers a list of chaotic models, progressing gradually from simple cases to more complex chaotic motion examples. For our study, I have chosen the model of a driven damped anharmonic oscillator. First, students acquainted themselves with the numerical monitoring of the motion, then they observed that the chaotic signals have never repeated themselves, so they were unpredictable. In a next step, I asked students to choose two initial conditions that differ only in the 4th decimal from each other and plot the positions, x, of the two cases as a function of time (the middle graphs in Figure 4.). They could see that the trajectories became dramatically different very soon. This was again an opportunity to observe butterfly effect in their own simulations. Playing with different representations students also learnt that the butterfly effect shows up in all chaos-related quantities, e.g., in the velocity (v) time series (lowest curves in Figure 4.) and in the phase space plots (uppermost curves).

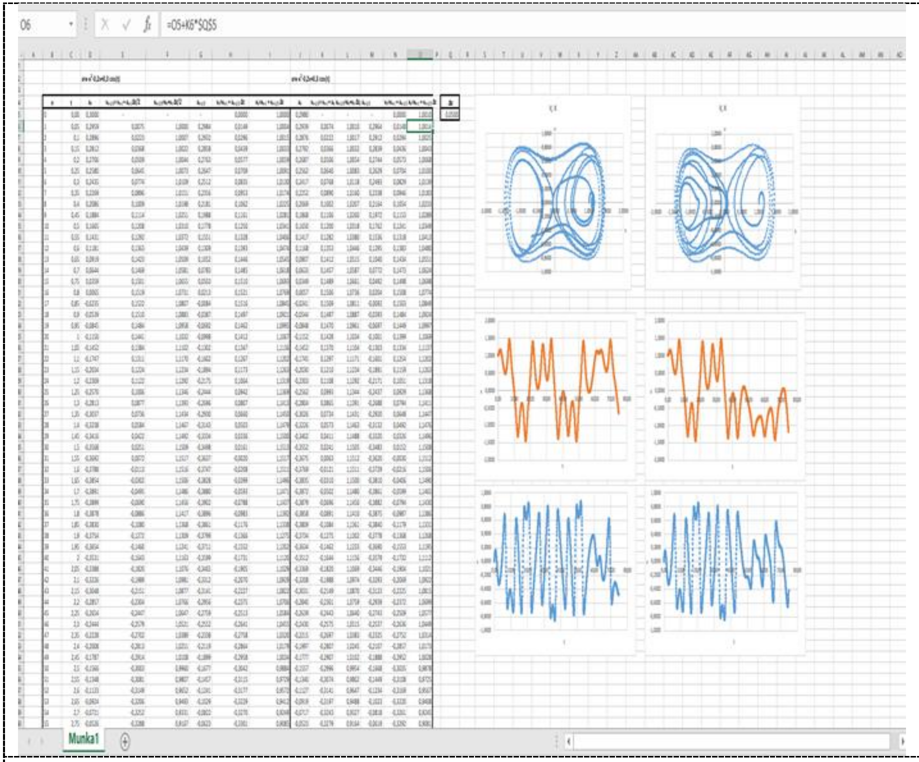

Figure 4. Numerical monitoring of motions with Excel worksheets: chaotic oscillators with two different starting points (differences only in the 4th decimal).

2.3. Free software packages

Ready-made software packages are also available on the internet. I used Dynamics Solver in my teaching module, which is a freely downloadable software designed specifically to simulate dynamical systems without any programming skills [9]. I found however, that students needed longer time to master this software, so I recommend using it only when no time constraints are present or with particularly engaged students. For most students, I opted instead for other, less time-consuming demonstration materials available on the internet, like PhET simulations, and a magnetic pendulum unit [10].

In summary, in terms of teacher-student interaction, in the phase of experiments a high degree of freedom was provided for the students in the spirit of enquiry-based learning. In contrast, when studying the butterfly effect, teacher instructions became necessary. In the final phase of the teaching module, digital investigation, both a freedom in experimentation and teacher guidance was available. In addition, when experiencing with the marbling technique a freedom of creativity was given.

3. Competences of physics teachers and activities needed to enhance efficiency

In Hungary, the use of Tracker is widespread: the students must be able to use the Tracker program in the oral part of the advanced level secondary school leaving exam, and thus it is also part of teacher education. There are two courses related to programing in the Hungarian teacher education: "Mathematical Methods in Physics", and "The use of computers" (titles as quoted are from Eötvös Loránd University Budapest). In the former, teacher-trainees become acquainted with numerical methods for solving differential equations and apply them in Excel worksheets, while in the latter they learn the elements of Phyton programming.

Based on our experience, it is not easy for teachers and teacher-trainees to understand the method of finite steps used in simulations. Nevertheless, lots of students are able to learn programing during their university years, but this knowledge is often not used later and students forget it. It could be very useful for teachers to attend conferences or workshops on the subject, at a certain specified level. These workshops should be practice oriented. In teacher education, a possible test could be adding a new questions to the closing examination topic list which requests students to detail all their nontrivial digital technology-related competences.

The competences a physics teacher should master are the ability of using digital technologies in a meaningful way in physics lessons, of using the internet effectively and being able to use programs for video-processing. The teacher should be familiar with software, like Tracker, that converts observations (or videos) into data or graphics and be able to use ready-made softwares (PhET simulations or something similar). It is an advantage for a teacher to be able to write programs as well, for example in Python or C++. If not, then Dynamics Solver is also a good possibility.

4. Complete multimedia materials to support the importance of butterfly effect in practice

In my chaos teaching module I also used two complete multimedia materials to explore the butterfly effect, in scientific terms the sensitivity to initial conditions, perhaps the most relevant feature of chaos.

4.1. An introductory e-learning webpage

The e-learning material we used [5] is structured according to the four important properties of chaos: temporal irregularity, unpredictability, structured patterns that appear in appropriate representations, and predictability in terms of probabilities. The material offers the possibility to explore chaos in a structured way along these four main features. A stated above, my focus was on butterfly effect, with special emphasis on its role as a representation of unpredictability.

In the teaching module we considered the case of a driven pendulum. In the experiment the point of suspension of the pendulum is moved horizontally with precise periodicity in time. The physical pendulum was represented by a ruler in this case. The motion of this pendulum is chaotic. In the e-learning web-site [5], first we watched video recordings of experiments carried out with this driven pendulum (Figure 5.).

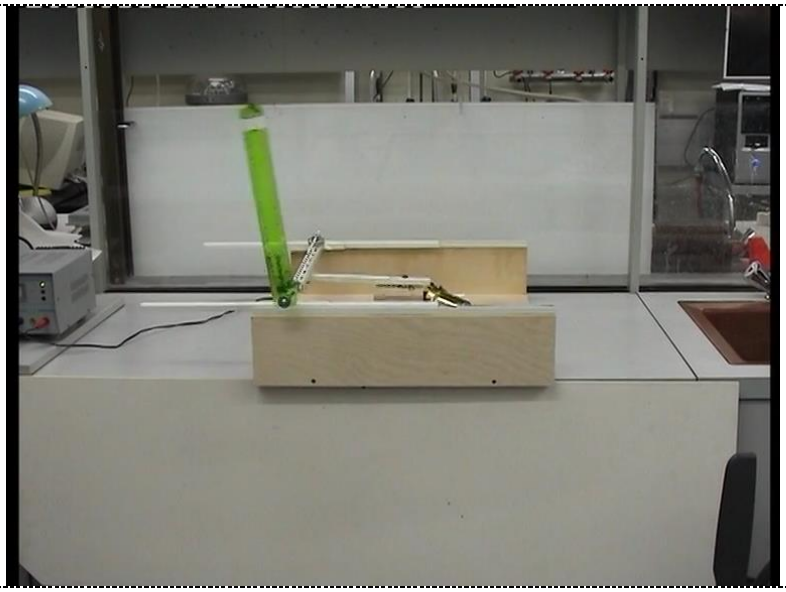

Figure 5. Driven pendulum with a ruler representing the physical pendulum (snapshot taken from a video of page [5]).

In a more advanced version of the experiments two, practically identical rulers are fixed to the same periodically moving axis, so that the rulers move in two parallel planes without collision. Even in the case when the movement of the two rulers start in a similar way, their motion becomes completely different in a short time. The explanation of the phenomenon is again the butterfly effect that can be observed visually in this case.

Besides movies of real experiments, the website offers images of simulated results. Such a picture is shown in Figure 6 that represents the motion of 11 identical rulers. The endpoints of the 11 rulers started in the same position with slightly different initial speeds. The students can observe butterfly effect again, this time in a precise numerical simulation.

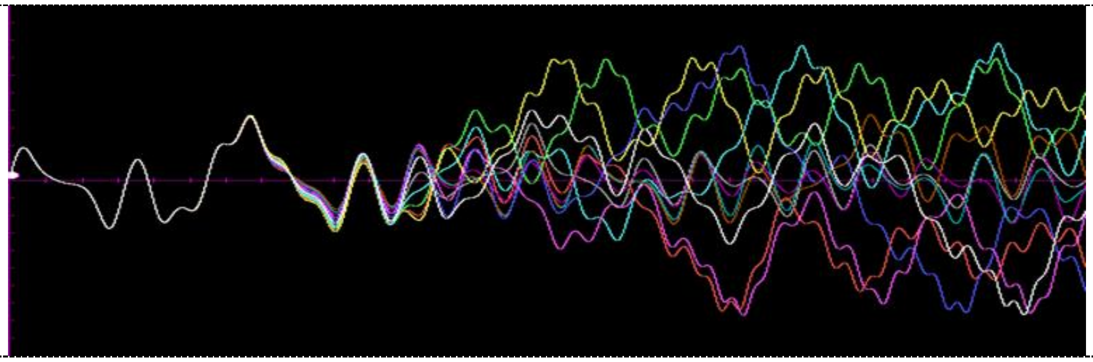

Figure 6. Driven pendulum: simulation with 11 identical rulers (picture taken from page [5])

In modern meteorological forecasts we encounter similar diagrams, summarizing the results of an ensemble of different simulations starting from nearly identical states of the atmosphere. From this e-learning material site we can reach the public page of German Weather Service [11]. We can select easily the desired geographical location, and graphs of the temperature and the precipitation forecast of the chosen location become visible for the next two weeks.

As an example, in Figure 7 we show the weather forecast for 25 September 2020, Malta. As long as the plotted line appears mainly white, the curves move together meaning that the expected weather is well predictable. From the point where the colours become discernible, the weather can evolve in quite different ways. This means that meteorological forecasts are only reliable for a few days: here 4 days. Students get a much deeper understanding of natural phenomena when they compare the predicted surface temperature graph with the graph of the 11 rulers' simulation and discover the common features in the two figures. In both cases, the curves move together for a short time. Students can observe that the movement of the pendulum cannot be predicted for long times, just like the weather. So they meet again the butterfly effect, here especially in the context of unpredictability.

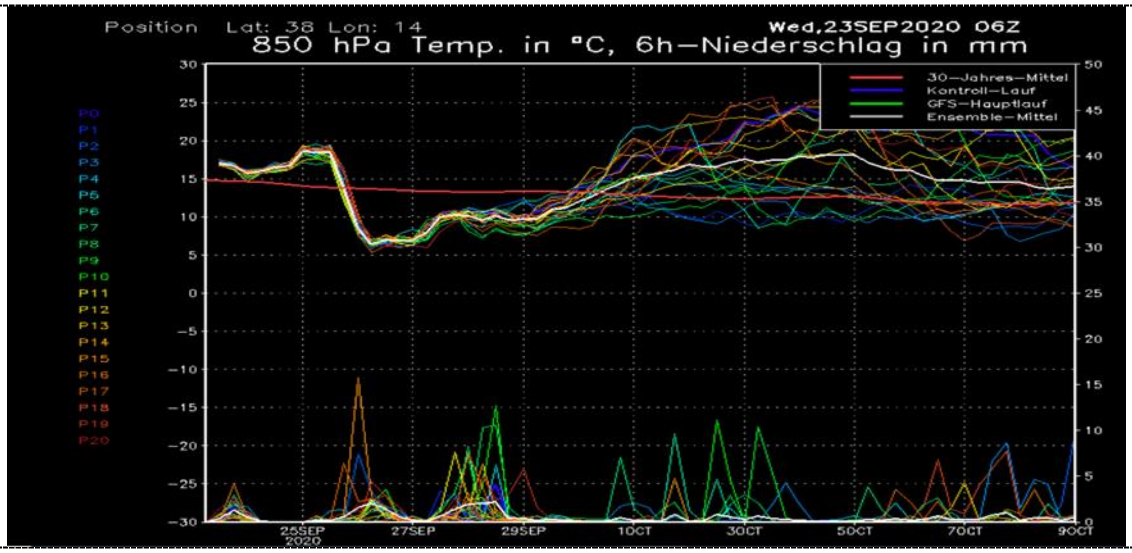

Figure 7. Weather forecast for two weeks starting on 25 September 2020 Malta: an ensemble of 50 different simulations starting from nearly identical states of the atmosphere (downloaded from [11])

4.2. A gamified approach

A whole new opportunity to teach chaos has emerged with the appearance of a program named RePLaT-Chaos [12] developed for high school students by a colleague [13], [14]. This program can be used to monitor the spreading of volcanic ash in the atmosphere (Figure 8.) utilizing observation-based wind fields.

Students can use individually the program's interface. They can choose any desired location or eruption condition as input parameter, and the simulation returns a map that beautifully demonstrates that the ash spreads along fractal filaments, similar to the cream being stirred in the coffee, only the sizes are different. As an example again, in the upper picture of Figure 9. We show a volcanic eruption generated close to Malta. On the bottom picture (Figure 9.) we can also observe that the relatively small initial length of 100 km of the pollutant cloud increased 10.000 times longer within 10 days.

The program is a very useful tool for students to explore chaotic properties of the spreading of environmental pollution in the air. It helps students to raise awareness on the importance of chaos in environmental phenomenon, and it is easy to use. Important properties of chaos, like the butterfly effect, can easily be demonstrated by this program.

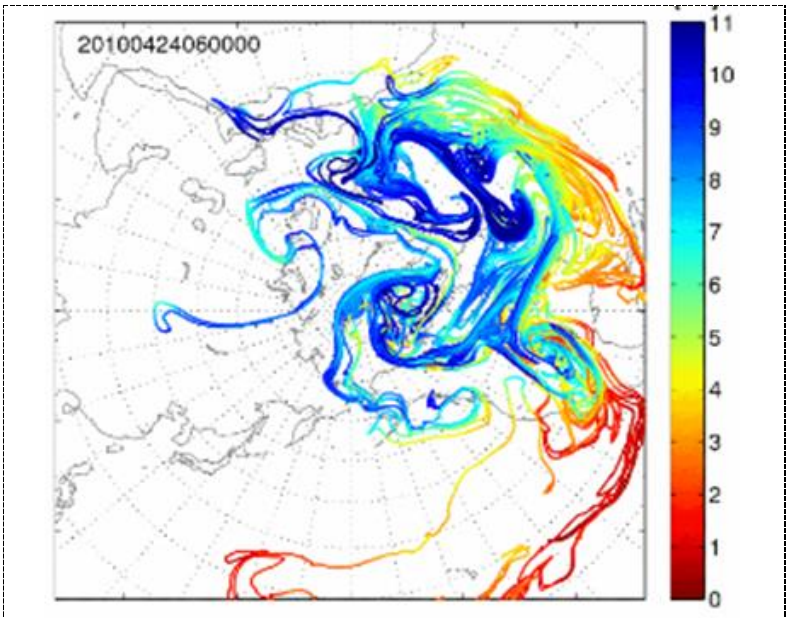

Figure 8. The simulation shows a gas cloud emanated from Fuji (Japan; 3776 m, Latitude: 35° 10' N Longitude: 138° 40' E) at 14 April 2010 after 10 days. Colours indicate heights (picture generated by the RePLaT-Chaos program [12])

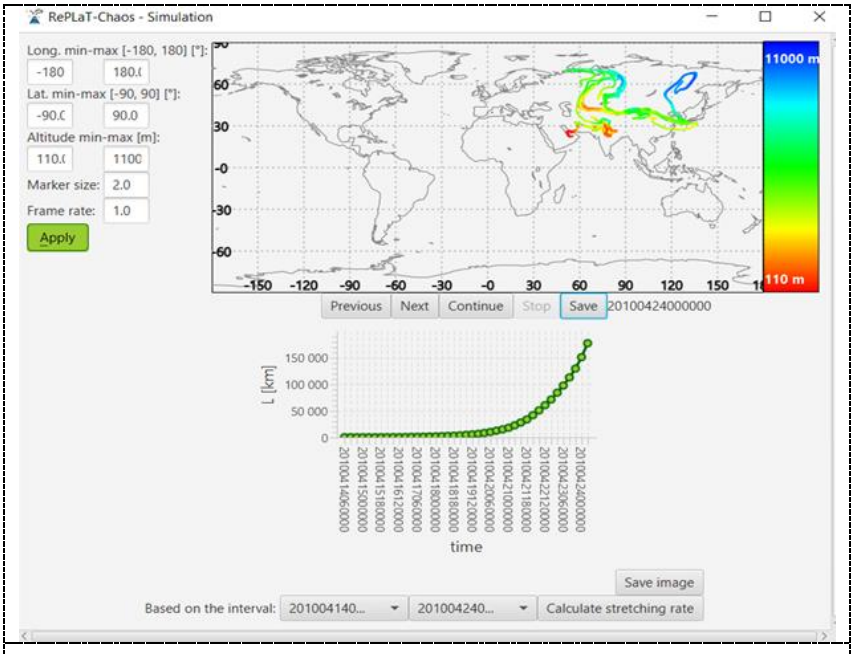

Figure 9. An eruption started close to Malta (Latitude: 35° N Longitude: 14° E) at 14 April 2014. Above: The simulation returns a map of the ash cloud; Bottom: The initial length grew 10.000 times longer after 10 days (picture generated by means of the RePLaT-Chaos program [12])

Since some of my students had difficulties with the ICT tools mentioned above, I tried RePLaT-Chaos, and this proved to be a complete success: the students used it with great enthusiasm.

As an outlook I would like to mention that handicraft is a very effective tool for becoming acquainted with chaos, and with the problem of dispersion of material in fluids. The marbling technique [15] involves mixing of paints on the surface of water. Using this technique, students experienced how patterns developed. We used the marbling technique [15] following the experiments and the simulations. After the hands-on activities we return to the topic of environmental flows. Students were able to recognize similar patterns when encountering environmental contamination. Structures similar to those seen in the marbling activity (Figure 10.) appear in environmental phenomena. Students have the possibility to compare the pattern of their handicraft and the pattern of oil contamination on the surface of water (Figure 11.) or during the spreading of volcanic ash in the atmosphere (Figure 8.).

Figure 10. Paint on the surface of water: chaotic mixing, generated in the process of marbling (picture taken by the author)

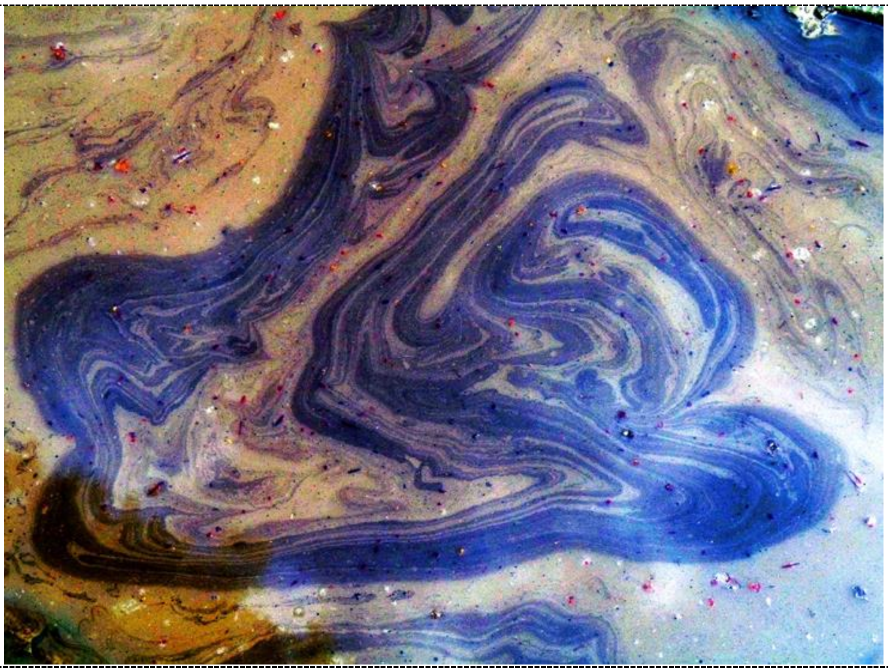

Figure 11. Oil contamination on the surface of water in nature (photo by Antonescu Traian)

5. Conclusions

We have experienced that students enrolled in the teaching module automatically gained a considerable amount of digital literacy and computer skills that can profitably be used in general physics courses and other fields as well. They became familiar with digitalized measurements as presented in section 2.1, and learned concepts of modelling and simulations, as shown in section 2.2. The RePLaT-Chaos program presented in section 4.2. raised their environmental awareness and sensitivity to global problems faced by humanity in the 21st century. The course also demonstrated that multimedia applications and gamified approaches can effectively help the acquisition of new concepts and enhance motivation for learning.

Our investigations also revealed what kind of competencies physics teachers need to have when using digital technologies (sections 3. and 4.): they should be able to use the internet in an effective and useful way, they should be familiar with programs for video-processing, they are expected to know software which can convert observations into data and graphics, they have to be prepared to use ready-made programs, and, finally, it would be advantageous to be able to write programs. In the present paper we provided a first-aid type digital toolbox, i.e., a minimal set of relevant technologies that teachers can use in teaching physics: programs to digitalize measured data (e.g. Tracker in section 2.1.), programs for simulations (e.g. Excel in section 2.2.), ready-made softwares (e.g. Dynamics Solver or PhET simulations), or a complex but easily manageable and accessible software, the RePlaT-Chaos program. All our experiences above show that, although chaos is not part of the physics curriculum, it is an exciting subject for high school students. It provides a good opportunity for the development of digital competences in teacher training, and it also helps to teach physics more effectively. Related to the article classifying the research of physics education [7], we suggest that teaching chaos physics should be included in teacher training education.

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