# A combination of historical Physics documents, combined with other teaching tools, for the instruction of perspective teachers about Chaos and Complexity.

**Aristotelis Gkiolmas[1], Artemisia Stoumpa[1], Constantine Skordoulis[1], & Anthimos Chalkidis[1]**

*[1]: Athens Science Education Laboratory (ASEL),*

*Department of Primary Education, University of Athens, Greece.*

**agkiolm@primedu.uoa.gr**

**Abstract.**
The present work presents thoroughly and analyses a didactic methodology for teaching aspects of Chaos and Complex Systems in Physics, to prospective Science educators. The methodology includes historical texts of Physics, experimental instrumentation, as well as computer models and simulations. The objectives are mainly to help undergraduate teachers realise the way that Physics evolves through changes and standoffs and the way in which the scientists work, which is much related to teaching the Nature of Science (NoS). At the same time, through this teaching methodology, there is an attempt to instruct undergraduate students about basic elements of Chaos Theory and Complexity Theory, by avoiding a heavy Mathematical formalism, incompatible with their age and their learning level and ability. The teaching sequence is intended to be applied in a pilot level to undergraduate students of the Department o Primary Education, University of Athens, so as to have initial qualitative and quantitative results.

**Keywords**
Teaching, Chaos, Complex systems, Complexity, Historical texts.

## INTRODUCTION

There is a growing tendency in contemporary Physics' education, to include in it aspects of (i) Chaos Theory, (ii) Complexity and (iii) Complex Systems' properties (Strogatz, 2014) and comportment.

Several attempts have been made or are being made to bring Chaos and Complexity into the school classrooms (Peitgen, Jürgens, Saupe, 2004; Peitgen et al., 1991; 1992; 1999), to popularise these Sciences (Briggs & Peat, 1989; Ruelle, 1993; Gleick, 2008) as well as to didactically transform certain concepts from them (Duit&Komorek, 1997; Duit, Komorek&Wilbers, 1998; Duit, Roth, Komorek&Wilbers, 1998)

The reasons for this aforementioned tendency are multiple: at first Chaos is a branch of modern Physics which concerns the average size-scales of Nature, the ones that we live in, thus they are relatively easy to notice and observe. This is in contrast with Relativity, which concerns, usually, the very large scales and with Quantum Mechanics, which mainly describes events in the microscopic world.

Secondly, Chaos, as a concept to be instructed, could bring significant changes to the ideas and the perceptions about everyday phenomena that the learning subjects may have. For instance, the involvement with Chaos theory abolishes the learner's belief that small causes have small effects and as the cause increases in size and significance, so does the effect (Lorenz, 1995; 2005; Smith, 2007). Additionally, Chaos theory give a big blowto the certainty that the same system with the same or similar pre-existing conditions, will evolve totally similarly (identically) I time (Lorenz, 1963; 1969; Prigogine, 1997; Stewart, 2002).

Thirdly, Chaos can, in certain easy ways, be produced and studied in the Physics' school laboratory. There are simple activities and kinds of equipment such as any Chaos Pendulum (Skordoulis et al., 2014; PASCO, 2017) that exist in many high schools.

Additionally Complex Systems and Complexity, in a variety of their aspects, arise in more and more scientific fields and in an increasing number of events of daily life (Kaufmann, 1995; Mitchell, 2009; Holland, 2014) together with the ideas that stem from these, such as cellular automata (Wolfram, 2002). The same is valid for Fractals, the mathematical representation of chaotic systems (Mandelbrot, 1982; Bountis, 2004).

It is obvious that if knowledge about Chaos, chaotic natural systems, Complexity and Complex systems is to be diffused into the school classrooms (mainly high-school classrooms but also Primary schools) a necessary prerequisite is to teach future teachers, as well as to train in-service Science teachers about them. This is the reason why the current research and the teaching methodology stemmingfrom it, focuses mainly on undergraduate Primary School teachers. The concepts related to Chaos and Complex systems that are intended to be taught to prospective Primary School teachers, have - necessarily - to be discharged from heavy mathematical formalism, and bring out mainly conceptual aspects to these fields of Physics. Such aspects are: the sensitive dependence on the initial conditions, the limited predictability, the existence of rules in apparently chaotic natural systems, the emergence of complex patterns based on simple rules, the act that "the whole is larger than the sum of its parts", the critical state (small change in the cause can cause great or unpredictable change in the results) etc.

## THE LEARNING SUBJECTS OF THIS TEACHING METHOD

The persons chosen to be taught issues about Chaos here are perspective Primary School Teachers (undergraduate students). It is an audience that possesses a little Mathematical and Science background, but it is of great research interest, we believe, because they transfer knowledge and stances about scientific fields to Primary School students, thus putting the foundations of the latters' affection and understanding for Science.

Additionally, it is considered as a challenge to instruct about Chaos using extremely limited mathematical formulation and Physics' terminology. Teaching sequence, have, thus to be created, which rely on optical representations, simulations, activities and narrations.

## METHODOLOGY AND TOOLS OF THE INSTRUCTON

Central to the methodology are the texts and documents written by the scientists themselves, on proceeding with facing Chaos for the first time. The two scientists studied for this purpose are Poincaré and Lorenz (Poincaré, 1914; Diacu, 1996; Lorenz, 2005). Using the texts of these two, students are driven to the contradictions, the gridlocks, the unexpected facts and the inexplicable results that led the scientists to the new scientific field (Chaos). A picture of the text of Poincaré that is being used is depicted in Figure 1.

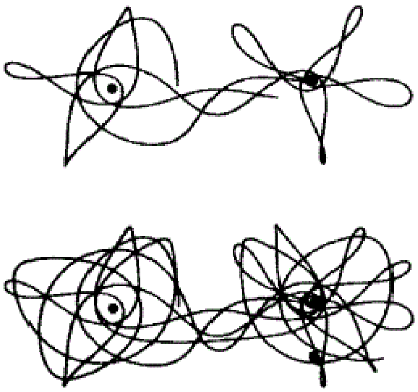

**Figure 1**.Indicative orbits in the three-body problem as drawn by Poincaré (Stewart, 2002)

The text of Poincaré used in the current teaching sequence refers to a cone that one makesit stand on its apex and then it falls (Poincaré, 1914)

*«…itseemsthatchancealonewilldecide. If the cone were perfectly symmetrical, if its axis were perfectly vertical, if it were subject to no other force but gravity, it would not fall at all. But the slightest defect of symmetry will make it lean slightly to one side or other, and as soon as it leans, be it ever so little, it will fall altogether to that side. Even if the symmetry is perfect, a very slight trepidation, or a breath of air, may make it incline a few seconds of arc, and that will be enough to determine its fall and even the direction of its fall, which will be that of the original inclination.*

*A very small cause which escapes our notice determines a considerable effect that we cannot fail to see, and then we say that that effect is due to chance. If we knew exactly the laws of nature and the situation of the universe at the initial moment, we could predict exactly the situation of that same universe at a succeeding moment. But, even if it were the case that the natural laws had no longer any secret for us, we could still only know the initial situation approximately. If that enabled us to predict the succeeding situation with the same approximation, that is all we require, and we should say that the phenomenon had been predicted, that it is governed by laws. But it is not always so; it may happen that small differences in the initial conditions produce very great ones in the final phenomena A small error in the former will produce an enormous error in the latter. Prediction becomes impossible, and we have the fortuitous phenomenon.»*(PoincareH.,1914, p 67-68)

The students discuss the notions of predictability or non-predictability, as presented in the text above, as well as the concept sensitive dependence on the initial conditions.

As a second example, students read in groups the famous extract from Lorenz (1995), where he describes how even small round-up approximations in very small decimal digits created Chaos inhis computer's outcomes of Meteorological values:

*"In Figure 43 [* note: Figure 2 for us here] we see a copy of fifteen months of the somewhatfaded original output, divided for display purposes into three five-monthsegments.*

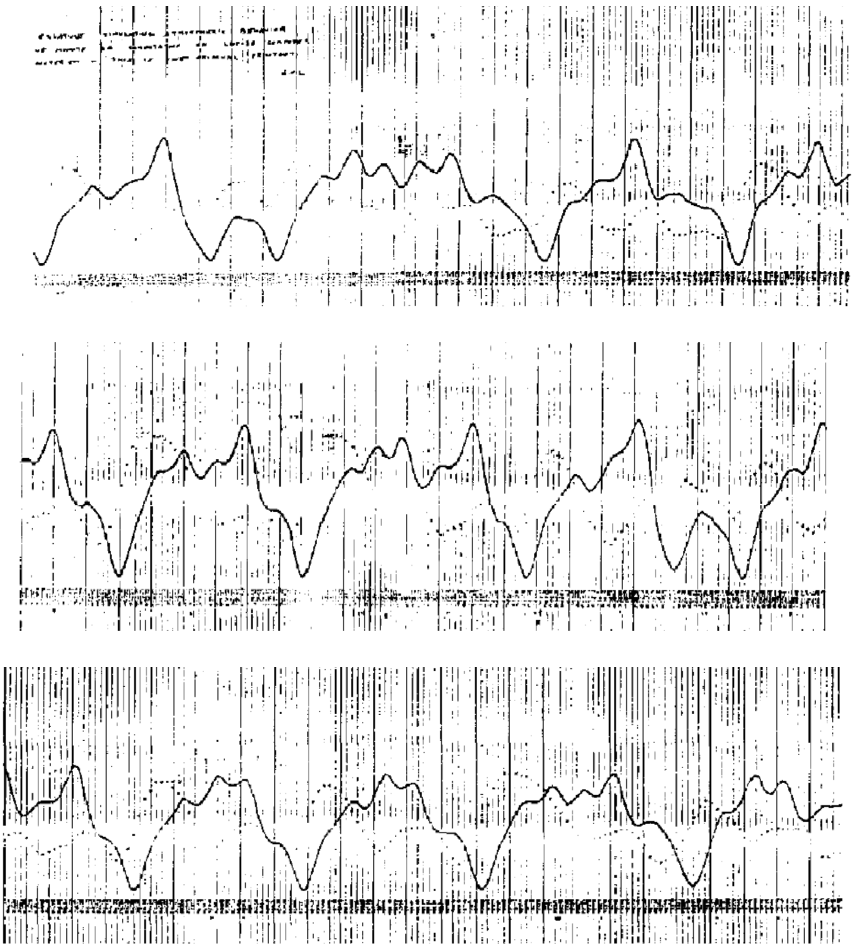

**Figure 2.** A fifteen-month sequence of the values of a meteorological parameter related to winds, as depicted in the computer of E.N. Lorenz (Lorenz, 2005; p.136)

*The chosen variable is an approximate measureof the latitude of the strongest westerly winds; a high value indicatesa low latitude. There is a succession of "episodes," in each of whichthe value rises abruptly, remains rather high for a month or so, andthen drops equally abruptly, but the episodes are not identical and are not even equal in length, and the behavior is patently nonperiodic. At one point I decided to repeat some of the computations in order to examine what was happening in greater detail. I stopped the computer, typed in a line of numbers that it had printed out a while earlier, and set it running again. I went down the hall for a cup of coffee and returned after about an hour, during which time the computer had simulated about two months of weather. The numbers being printed were nothing like the old ones. I immediately suspected a weak vacuum tube or some other computer trouble, which was not uncommon, but before calling for service I decided to see just where the mistake had occurred, knowing that this could speed up the servicing process. Instead of a sudden break, I found that the new values at first repeated the old ones, but soon afterward differed by one and then several units in the last decimal place, and then began to differ in the next to the last place and then in the place before that. In fact, the differences more or less steadily doubled in size every four days or so, until all resemblance with the original output disappeared somewhere in the second month. This was enough to tell me what had happened: the numbers that I had typed in were not the exact original numbers, but were the rounded-off values that had appeared in the original printout. The initial round off errors were the culprits; they were steadily amplifying until they dominated the solution. In today's terminology, there was* *chaos. It soon struck me that, if the real atmosphere behaved like the simple model, long-range forecasting would be impossible. The temperatures, winds, and other quantities that enter our estimate of today's weather are certainly not measured accurately to three decimal places, and, even if they could be, the interpolations between observing sites would not have similar accuracy. I became rather excited, and lost little time in spreading the word to some of my colleagues. In due time, I convinced myself that the amplification of small differences was the cause of the lack of periodicity. Later, when I presented my results at the Tokyo meeting, I added a brief description of the unexpected response of the equations to the roundoff errors."*(Lorenz E. 2005, p. 134-135)

Then, in the worksheets, there is discussion and questions about this historical text.

As an auxiliary tool instruments such as a Chaos Pendulum (PASCO, 2017) and forms of software like NetLogo (Wilensky, 1998; 1999) are utilized to represent what is chaotic and/or complex system's comportment in real circumstances. In Figures 3 and 4, images of the aforementioned teaching tools are shown.

**Figure 3.**One type of "Chaos Pendulum", used for didactic purposes (PASCO, 2017**)**

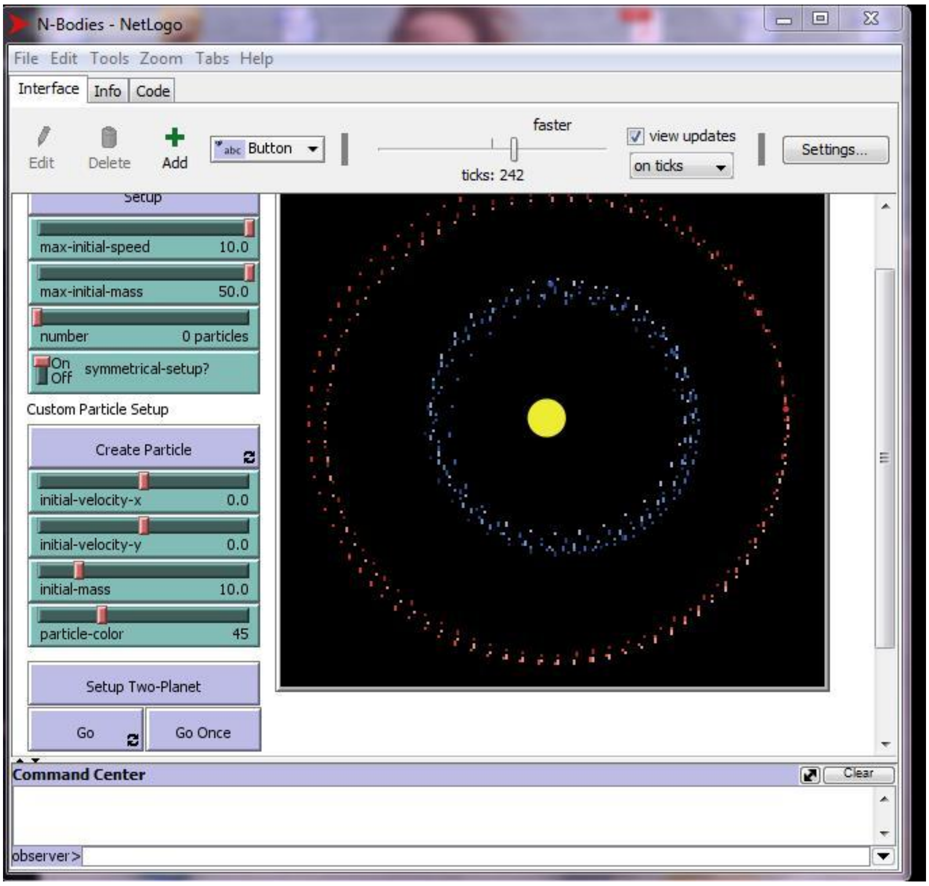


**Figure 4.**A screenshot of an initial stage of the model of the N-bodies problem in NetLogo (Wilensky, 1998)

Finally, activities with pen and pencil and paper or with simple materials (Peitgen et al., 1991) help the learning subjects to "create" chaotic conditions or time-evolutions and patterns, by themselves.One such activity is the "chaos game", depicted in Figure 5.

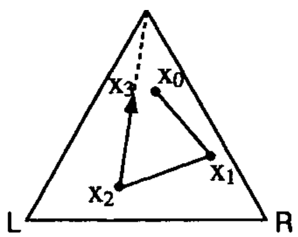


**Figure 5.**An early-stage drawing of the Chaos Game" (Peitgen et al., 1991; p. 37)

**THE SCHEDULED TEACHING INTERVENTION (TEACHING SEQUENCE) ABOUT CHAOS AND COMPLEXITY.**

There are five steps in the teaching sequence and in the Worksheets:

- Initial raise of interest with questions and visual material.
- Studentsinteract and read the documents (extracts) of the scientists..

- Students take measurements and make graphic representations with the chaos pendulum.
- Playing with NetLogo to realize and conceptualisechaotic behavior as well as certainaspects of Complex Systems, such as percolation, (Wilensky, 1997).
- Stage of drawing conclusions, of consolidation and of extensions to everyday lifeand students' actual surroundings.

The overall teaching sequence is based on the inquiry-based-learning model (Bybee et al., 2006)

## CONCLUSION

The pre-existing undergraduate students' ideas about Chaos, Complex Systems and Complexity, the method of instruction used to rephrase them and their new (aimed at) ideas in the teaching sequence presented in this work, are shown in Table 1.

**Table 1.**Change of the ideas of the undergraduate students, through the instruction about Chaos and Complex systems.

| **Initial Students' Idea and/or Concept** | **Method used in this research (teaching sequence) in order to change it** | **Final idea and /or Concept after the instruction** |
|---|---|---|
| Phenomena with similar start will evolve similarly | Historical text, NetLogo, Chaos Pendulum | Phenomena with similar start can evolve very differently |
| There are no rules in Chaotic Behavior and chaotic orbits | Historical text, NetLogo, Chaos Pendulum | There is certain "order" in Chaos |
| Science can make extremely accurate predictions | Historical text | Science can make predictions with limited accuracy, and this sometimes produces "Chaos". |
| Simple rules create simple aggregate outcomes | NetLogo | Simple rules can create very complex (emergent) outcomes |
| Small change in a cause results in a small change in the effect. | Historical text, NetLogo, Chaos Pendulum | Small change in a cause can result in tremendous or unpredictable changes in the effect. |

## HISTORICAL PHYSICS' TEXTBOOKS(whose extracts have been used):

Poincaré, H.(1914).*Science and Method*.[Translated in English by Francis Maitlad]. London, Edinburgh, Dublin & New York: Thomas Nelson and sons.
Lorenz, E. (2005).*The Essence of Chaos*.London.*UCL Press*. ISBN 0-203-27116-5 (Adobe e-Reader Format) First published in 1993 by the University of Washington Press.

## REFERENCES


Bountis, Tassos. (2004).*The Wonderful World of Fractals: A tour in the New Science of Chaos and Complexity*. (Greek language).Athens, Greece: LeaderBooks.
Briggs, J., Peat, F., D. (1989).*Turbulent Mirror: An illustrated guide to Chaos Theory and the science of wholeness*.New York: Harper & Row.
Bybee, R. W., Taylor, J. A., Gardner, A., Van Scotter, P., Powell, J. C., Westbrook, A., &Landes, N. (2006). *The BSCS 5E instructional model: Origins, effectiveness, and applications*. Colorado Springs: BSCS.
Diacu, F. (1996.*)*The solution of the n-body Problem. *The Mathematical Intelligencer***18** (3),*66–70.*
Duit, R., &Komorek, M. (1997).Understanding the basic ideas of chaos-theory in a study of limited predictability.*International Journal of Science Education* **19**, 247–264.
Duit, R., Komorek, M., &Wilbers, J. (1997).Studies on educational reconstruction of Chaos theory.*Research in Science Education***27**,339–357.
Duit, R., Roth, W.-M., Komorek, M. and Wilbers, J. (1998). Conceptual change cum discourseanalysis to understand cognition in a unit on chaotic systems: towards an integrativeperspective on learning in science. *International Journal of Science Education***20**, 1059–1073.
Gleick, J. (2008). *Chaos: Making a new Science*. New York: Penguin Books.
Head, B. and Wilensky, U. (2017).NetLogo Chaos in a Box model.http://ccl.northwestern.edu/netlogo/models/ChaosinaBox. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.
Holland, J. (2014). *Complexity: A very short introduction*. Oxford: Oxford University Press.
Kaufmann, S. (1995).*At Home the Universe: The Search for the Laws of Self – Organization and Complexity*. New York: Oxford University Press.
Kellert, S., H. (1994). *In the Wake of Chaos: Unpredictable Order in Dynamical Systems.* Chicago: The University of Chicago Press.
Lorenz, E., N. (1963).Deterministic Nonperiodic Flow. *Journal of the Atmospheric Sciences* **20** (2), 130–141.
Lorenz, E., N.(1969).*Three approaches to atmospheric predictability". Bulletin of the American Meteorological Society***50**, *345–349.*
Lorenz, E., N. (1995).*The Essence of Chaos*. Seattle: University of Washington Press.
Mandelbrot, B. (1982).*The Fractal Geometry of Nature*.Canada: W. H. Freeman and Company.
Mitchell, M. (2009).*Complexity: A guided tour*. New York: Oxford University Press.
PASCO (2017) Chaos Experiment.Retrieved by: https://www.pasco.com/prodCatalog/EX/EX-5523_chaos-experiment/index.cfmon 15th October 2017.
Peitgen H-O., Jürgens, H., Saupe, D., Maletsky, E., Perciante, T, Yunker, L. (1991). *Fractals for the Classroom: Strategic Activities Volume One*. New York: Springer-Verlag.
Peitgen, H-O, Maletsky, E., M., Jürgens, H., Perciante, T., Saupe, D., Yunker, L. (1992).*Fractals for the Classroom: Strategic Activities,* Volume 2. New York: Springer.

Peitgen, H-O, Maletsky, E., M., Jürgens, H., Perciante, T., Saupe, D., Yunker, L. (1999).*Fractals for the Classroom: Strategic Activities*, Volume 3. New York: Springer.
Peitgen, H-O., Jürgens, H., &Saupe, D. (2004).*Chaos and Fractals: New Frontiers of Science*. 2nd Edition. New York: Springer – Verlag.
Poincaré, H. (1948). *Science and Method*.New York: Dover.
Poincaré, H. (2001*). The Value of Science: Essential Writings of Henri Poincaré*. New York: Modern Library Science.
Poincaré, H. (2017a). *Science and Hypothesis*.CreateSpace Independent Publishing Platform.
Poincaré, H. (2017b).*The Three-Body Problem and the Equations of Dynamics: Poincaré's Foundational Work on Dynamical Systems Theory*. Translation: Bruce D. Popp. Switzerland: Springer International Company.
Prigogine, I. (1997).*The End of Certainty: Time, Chaos and the New Laws of Nature*.New York: The Free Press.
Ruelle, D. (1993). *Chance and Chaos*. Princeton, New Jersey: Princeton University Press.
Skordoulis, C., Tolias, V., Stavrou, D., Karamanos, K., &Gkiolmas, A. (2014).Teaching Chaos with a Pendulum to Greek Secondary School Students.*Advances in Systems Science and Applications***14** (2), 158-169.
Smith, L. (2007).*Chaos: A Very Short Introduction*. 1st Edition. Oxford: Oxford University Press.
Stewart, I. (2002). *Does God play Dice? The New Mathematics of Chaos*.2nd Edition. Oxford: Blckwell Publishing.
Strogatz, S., H. (2014). *Nonlinear Dynamics and Chaos: With Applications to Physics, Biology, Chemistry and Engineering (Studies in Nonlinearity)*. 2nd Edition. Boulder, Colorado: Westview Press.
Wilensky, U. (1997). NetLogo Fire model.http://ccl.northwestern.edu/netlogo/models/Fire. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.
Wilensky, U. (1998). NetLogo N-Bodies model.http://ccl.northwestern.edu/netlogo/models/N-Bodies. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.
Wilensky, U. (1999). NetLogo.http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, IL.
Wolfram, S. (2002).*A New Kind of Science*.Wolfram Media.