

EDUCATING TO COMPLEXITY: A CHALLENGE

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Je tiens pour impossible de connaître les parties en tant que parties sans connaître le tout, mais je tiens pour non moins impossible la possibilité de connaître le tout sans connaître singulièrement les parties.

Blaise Pascal – Pensées

Abstract

Education today faces difficult tasks: the traditional model of science education - disciplinary, analytical and deductive - is challenged by the complexity of the world to be deciphered and the complexity of the science to be communicated. Yet, more than ever, a scientific knowledge is needed for everyone. Some aspects and examples of this modern challenge shall be discussed, dealing with primary, secondary and post-secondary education.

Introduction

The physicist and Nobel laureate (1926) Jean Perrin first demonstrated experimentally in 1908 that atoms existed. For him, science was a way *to replace the complexity of what is seen by the simplicity of the invisible*. As any child, any student apprehends the world while perceiving it by the senses, an education aimed at understanding and eventually mastering science is exactly confronted to this step, namely to jump from the visible to the invisible. One has to move from the real object to the mental object, from the concrete to the abstract, from the obvious to the counter-intuitive. Even if today, we can show pictures of atoms in crystals or proteins to our students, the invisible is still there, hidden in the quarks, the dark matter, the equations and the symbols. Science education is difficult, because we can say with Gaston Bachelard that “*There is no such thing as the simple, we just know the simplified*”. And science education becomes more difficult, as the complexity of science immensely increases.

Traditional science education aims at training specialists, focusing on excellence in one discipline such as physics, with little or no exposure to epistemology or philosophy. But today, the complexity of modern physics (or biology) and the ethical issues met by the applications of physics (or biology) question this traditional approach. Traditional education pays more attention to technical ability or learning facts than to the understanding of what is a scientific process. But today, the importance of science and technology in the life of every citizen also questions this traditional attitude.

In front of such inadaptations, deep changes may be necessary. In a first section, with a few examples, I give some signs detailing why these changes are needed. In the second one, I examine possible evolutions for an advanced science education, with some examples in physics, my own field. In the third, I discuss how the goal of a *science for all* reintroduces the person to the objective realm of natural sciences, and forces one to abandon over-specialized subjects for an interdisciplinary vision of education. I will focus essentially on primary and secondary education, but many observations may also apply to tertiary education.

1. A new vision of sharing science

Traditionally, science education aims at preparing a small number of specialists, mastering a well-defined field of knowledge. Because of the ever growing complexity and abstraction of the concepts, a hyper-specialization of individuals is practiced and keeps increasing. Related to this complexity, modern and central concepts in physics, such as special or general relativity, or quantum mechanics, are so distant from familiar representations of nature that secondary education often ignores them, transmitting a physics apparently simpler, but older than a century and disconnected from today's applications.

In addition, physics education observes a strict, although recent (20th century), separation between the objectivity of natural sciences and the various facets of subjectivity explored by the humanities. As a consequence, in our secondary or post-secondary lectures when training physicists, the historical emergence of scientific concepts, the epistemological difficulties, the interfaces with other fields such as biology or neurosciences are often ignored, not even to speak of ethics. Developed countries are facing a serious shortage of students choosing to study physics at the end of secondary school (Depp 2012), and one may question whether there is not here a causal relation with the way physics is presented to them.

On top of this, a new challenge emerged in the last two decades. Today, science and technique invade almost every aspects of individual life, deeply modify our representations of nature, impact the development of societies and aim at shaping the future. The whole society is concerned by such a massive transformation and a good science education for all students on our planet is requested. But implementing such a *science for all* education faces two difficulties.

The first difficulty occurs when science has to deal with societal issues where scientific disciplines are mixed in intrinsically complex and challenging problems, often highly non-linear: climate or energy issues are good examples.

Contrary to the classical separation of science in disciplines being taught separately, a cooperation, even at an elementary level, between different fields of knowledge is needed to help understanding or solving these complex problems (Morin 2005). The probabilistic or statistical aspects are also present, e.g. in health issues (vaccination, epidemics), natural or human-related extreme events (earthquakes, nuclear accidents), financial decisions. Here, interdisciplinarity seems the unescapable road education has to explore.

The second difficulty deals with the intrication of objectivity and subjectivity in these issues. Indeed science may provide objective answers: e.g. Is global warming real? Is it caused by an increasing carbon dioxide concentration? What is the probability of a nuclear accident? On the other hand, choices made by citizens involve many subjective factors, face hazards of all sorts, meet with religious convictions and are deeply entangled in the person's subjectivity. The good old separation between the object and the subject seems no longer to work. Here, a reconciliation between the person and the scientific knowledge seems the road to explore (Serres 2011).

Hence, as science itself is moving further and further into the realm of complexity, making it more difficult to be explored, to be taught, understood or mastered, science education has to think itself anew (Sánchez Sorondo *et al.* 2007).

2. Teaching advanced science

In the following and with a few examples, I question how high quality scientific training could give students (from secondary to bachelor level) a solid basis to lead a professional life as scientists, without remaining blind to the global development of a complex science or to the complex expectations of the society. Namely: to master the tools of a specialized domain, in order to use them efficiently; to know and understand the conceptual revolutions (epistemology) which have led to modern physics; to stimulate their creativity by avoiding to format them; to open their mind to the borders between disciplines, to the unexpected analogies and metaphors which, in the past, have often led to great discoveries (history); to foster a sense of ethical issues, both internal to science (respect of truth and modesty) and external (applications of science).

A century ago, special relativity shook the classical visions of space and time, built by human brains on the basis of their concrete experience. Teaching a relativistic world encounters deeply embedded representations, which often hamper the student's understanding or creativity. After the *thought experiments* of Einstein, Victor Weisskopf in the 1960s had already adressed this difficulty (Weisskopf 1960). I quote here an interesting use of the new tool

called augmented reality,¹ from a recent PhD project developed by Tony Doat (Doat 2012) and used for undergraduate students (De Hosson *et al.* 2011, Ladeveze *et al.* 2012). Palets or pucks on a carom billiard table are put in motion by a cue and hit, the velocity of light being brought to 1 m/s. Several frames of reference are available for the spectator, who is fully immersed in a 3-dimensional scene, each frame being seen with its own time and relative velocity (Fig. 1). Collisions are observed at will from the different frames, while the observer frame, with its 6 degrees of freedom, is constantly monitored by infrared sensors and computed. In addition to the understanding of kinematics, a haptic cue provides a direct muscular feeling of the dynamical properties encountered in special relativity.

This example, using augmented reality, is far from unique. The power of computers allows to make concrete for students and researchers the modern complexity of scientific domains, such as fluid dynamics (Crane *et al.* 2007), or plant growth (Diao *et al.* 2012).

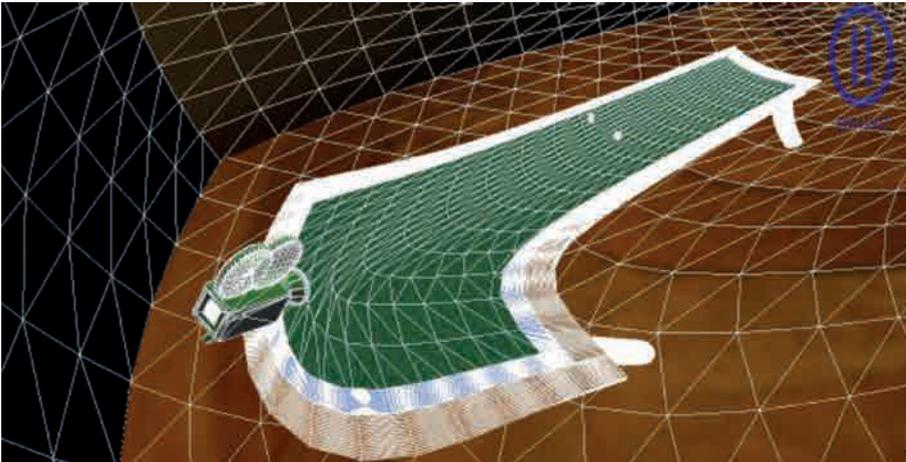


Figure 1. A scene being deformed under the relativistic aberration of light (From Doat T, PhD Thesis, 2012).

¹ Following Wikipedia's definition, **augmented reality** is a live, direct or indirect, view of a physical, real-world environment whose elements are *augmented* by computer-generated sensory inputs such as sound, video, graphics or GPS data. It is related to a more general concept called mediated reality, in which a view of reality is modified (possibly even diminished rather than augmented) by a computer. As a result, the technology functions by modifying one's current perception of reality.

Simply observe the slow and timid pace with which the complexity of quantum physics penetrates secondary schools in France, despite three Nobel prizes in our country on the subject (Alfred Kastler, Claude Cohen-Tannoudji, then Serge Haroche in 2012). A careful study of French physics textbooks over the last fifty years shows a slow, extremely cautious and mostly qualitative presentation, on the prerequisite that the adequate mathematical language of quantum physics was not then available to students (Lo Bello 2012).

My second example deals with the compartmentalized manner in which many science introductory courses are commonly taught. *Students fail to view even physics itself as a coherent of structure knowledge. This failure suggests that students would not be able to relate what they study in physics to phenomena encountered in other fields such as chemistry and biology* as expressed in a recent paper by a group of Jerusalem physicists and education researchers (Langbeheim *et al.* 2012). Reforms in universities are addressing this failure, with the goal of motivating students to focus on complex systems, without neglecting the necessary core of disciplinary contents. This group proposes an interesting integrated unit on soft matter. Typical topics in soft matter,

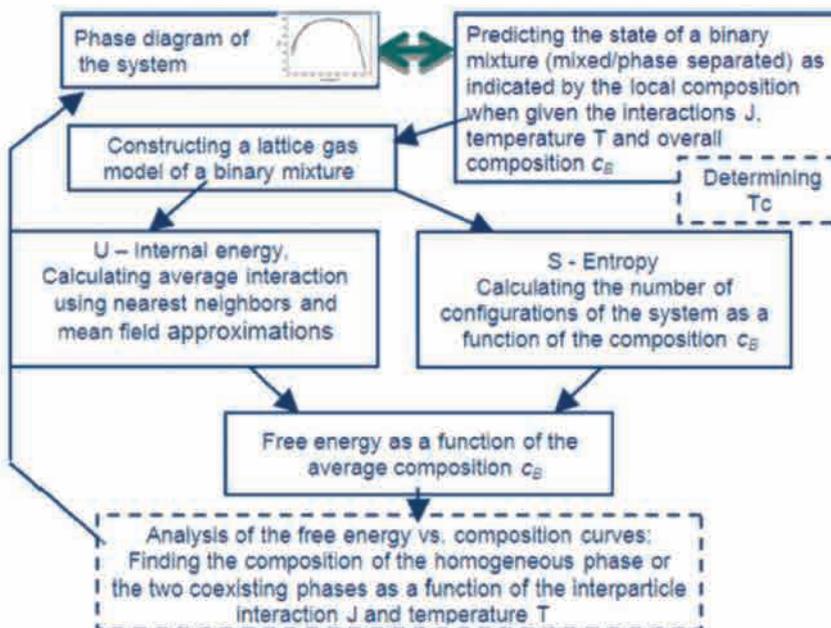


Figure 2. Soft matter: a proposed concept map for the derivation of free energy in a binary mixture (from Langbeheim *et al.* 2012).

such as the conformation of polymers in solvents, the cause of bending energy and shapes of membranes require thermodynamics and chemistry (Fig. 2). Despite the complexity of the objects, such study of soft matter, with an inquiring pedagogy, can focus on everyday materials which are familiar to students and important in materials science and biology.

My third example deals with language. It represents another communication difficulty introduced by the complexity of modern science. Traditionally, a language made of differential/integral calculus and chemical symbols was sufficient to cover most, if not all science. Today, in physics, electronics (descriptive tools), chemistry, biology (genes), quantum mechanics (Feynman diagrams), the multiplication of symbolic tools create barriers between disciplines. Some introduction of the students to epistemology, including elements of a general theory of language, would bridge this gap and help moving into the expression of abstract concepts (Dowek 2012).

3. Science for all students

In the introduction, I underlined the challenge of a renewed science education preparing all students to deal with complex issues involving science and society, accounting for the complexity of science itself. In the last two decades, this theme has been addressed by numerous reports at international levels such as OECD, UNESCO (UNESCO 2010), regional (European Union, Rocard 2007) or national levels (Royal Society 2010) as well as by the Pontifical Academies (Sánchez Sorondo *et al.* 2007). Without entering here into the richness that these detailed analyses provide, I would focus on the concept of *big ideas* in science.

When observing the complex world surrounding them and interacting with it, babies and children ask questions which, in their freshness and spontaneity, represent the early seeds of the whole scientific venture (Gopnik *et al.* 2000). Later, becoming adults, many will give up this curiosity and decide that science, its language and its machines, as often presented by the media, are too complex to be understood. They may even enter into relativism, forgetting that science is a search for truth. Or, conversely, discouraged by the complexity, they may entirely rely on the word of experts, renouncing their prerogatives of free thought.

How can we conceive the goals of science education (K-9 or so) for modern pupils facing this complexity? Not in terms of knowledge of a body of facts and theories but as a progression towards key ideas which together enable the understanding of events and phenomena which are of relevance to students' lives and later to citizen's. This vision of 'big ideas' in science (Millar R. & Osborne J 1998) emerged in the 1990s and was explored in

depth in a recent effort (Harlen 2011) built around the Interacademy Panel (IAP) Science education program, in parallel with the worldwide development of an inquiry pedagogy (Allende & Léna 2012) - in the spirit of *La main à la pâte* as developed in France (Charpak *et al.* 2005, Léna 2012).

I use here the term ‘idea’ to mean an abstraction that explains observed relationships or properties. A *big idea* in science is an idea that applies to a wide range of related objects or phenomena, whilst what we might call *smaller ideas* apply to particular observations or experiences. For instance, that worms are well adapted to living in the soil is a *small idea*; a corresponding *big idea* is that living things have evolved over very long periods of time to function in certain conditions. *Big ideas*, with their rich and wide encompassing power, not only provide explanations of observations and answers to questions that arise in everyday life when facing complexity, but they also enable a prediction capability to deal with previously unobserved phenomena. *Big ideas* are more abstract than small ones, they require more elaborate cognitive abilities, which are age- and intelligence- dependent. Science education has therefore to establish adequate progressions as for example it has been proposed for genetics at grades 5 to 10 (Duncan R.G. *et al.* 2009).

Table 1 presents a preliminary result of the exercise, aiming at a reasonably short list of big ideas, to be progressively explored from kindergarten to 9th grade.

Table 1
Big ideas on science, for K-9 or K-12 education
All material in the world is made of very small particles
Some objects can affect other objects at distance
Changing the movement of an object requires a net force acting on it
Energy is transformed when things change or are made to happen but the total amount of energy in the Universe is always the same
The composition of the Earth and its atmosphere shape the Earth’s surface and its climate
Our solar system is a very small part of one of millions of galaxies in the Universe
Organisms are organised on a cellular basis
Organisms require a supply of energy and materials for which they are often dependent on or in competition with other organisms
Genetic information is passed down from one generation of organisms to another
The diversity of organisms, living and extinct, is the result of evolution

But to understand how science seizes complexity, ideas *about* science must also be conveyed. Table 2 proposes four of them.

Table 2
Big ideas about science for K-9 or K-12 education
Science assumes that for every effect there are one or more causes
Scientific explanations, theories and models are those that best fit the facts known at a particular time
The knowledge produced by science is used in some technologies to create products to serve human ends
Applications of science often have ethical, social, economic and political implications

Conclusion

With the triple irruption of complexity in modern natural sciences themselves, in their transmission and in their interfaces with society, scientists meet a new and difficult responsibility, if they wish their activity to remain recognized, respected and understood. The primary goal of science, namely the search of the truth and the creation of adequate languages to express it remains indeed unchanged. But a new articulation has to be found between this quest of objectivity and the subjectivity of our contemporaries, whether they are themselves scientists or simple laymen.

We had a classical methodology, quantitative, deductive, determinist and reductionist, which has proven its efficiency. Even when it keeps demonstrating its value in dealing with the complexity of the cosmos, the cell, the history of life or climate, it may meet today certain limits. The modern subject, becoming himself/herself an object for science and technology, resists.

I conclude by quoting a very recent editorial published in the French newspaper *Le Monde*, signed by a reputed surgeon under the title “Biology and homoparentality”: *Experience shows that the speed at which one slides from the “forbidden” to the “tolerated”, the “allowed”, or even the “mandatory” essentially depends on the rhythm of scientific discoveries, no matter what the ethical issues are.* It seems to me that the question of the complex interaction between modern science and the person cannot be expressed in a better way.

References

- Alexandre L. (2012) “Biologie et homoparentalité”, *Le Monde*, Paris, 25-10-2012, l.alexandre@dnavision.be
- Allende J., Léna P. (2012) “Inquiry-based science education: developments in the secondary school and stimulating new assessment procedures”, *Science*, in preparation.
- Charpak G., Léna P., Quéré Y. (2005) *L'Enfant et la science*, O. Jacob, Paris.
- Crane K. et al. (2007). “Real-time simulation and rendering of 3d fluids”. GPU, Gems 3, pages 633-675.
- De Hosson, C., Doat T., Kermen, I., Parizot, E., Vézien, J.-M. “Designing learning scenarios for 3D virtual environment: the case of special relativity”, International Conference on Physics and Education, August 2011, Mexico City, Mexico.
- Diao J. et al. (2012) “Simulation of the topological development of young eucalyptus”, *Electronics in Agriculture* 80, 105-114. doi: 10.1016/j.compag.2011.10.019. url: <http://hal.inria.fr/hal-00651975>
- Doat T. (2012) *Espaces virtuels pour l'éducation et l'illustration scientifique*, Thèse de doctorat, CNRS-LIMSI, Université Paris-Sud.
- Dowek G. (2012) “Enseigner les sciences au XXI^e siècle”, *Terminal, technologie de l'information, culture et société*, Paris, in press. <http://www.revue-terminal.org/>
- Duncan R.G., Rogat A.D., Yarden A. (2009) “A learning progression for deepening student's understanding of modern genetics across the 5th-10th grades”, *J. Res. Sci. Teaching*, 46, 655-674.
- Gopnik A., Meltzoff A., Kuhl P (2000) *The scientist in the crib: What early learning tells us about the mind*, William Morris.
- Harlen W. (ed.) (2010) *Principles and big ideas in science education*, with contributions from Bell D., Deves D., Dyasi H., Fernandez de la Garza G., Léna P., Millar R., Reiss M., Rowell P., Wei Y., <http://www.ase.org.uk/bookshop/new-books/>. Translated into French, Spanish, Chinese, Serbian, Portuguese.
- Ladeveze, N., Doat T., Parizot E., Vézien J.-M. Learning Special Relativity Energy Laws Using Visio-Haptic Illusion. In: Proceedings of Workshop on Perceptual Illusions in Virtual Environments (PIVE, 2012), March, 2012, Costa Mesa, California, USA.
- Langbeheim E., Livne S., Safran S.A., Yerushalmi E. (2012) “Introductory physics going soft”, *Am. J. Phys.* 80, 51.
- Léna P. (2012) *Enseigner, c'est espérer. Plaidoyer pour l'école de demain*, Le Pommier, Paris.
- Les bacheliers S: des poursuites d'études de plus en plus dispersées* (2012), DEPP, Note 12.10, Ministère de l'éducation nationale, Paris. <http://www.enseignementsup-recherche.gouv.fr/pid24683-cid61231/les-bacheliers-s-des-poursuites-d-etudes-de-plus-dispersees.html>
- Lo Bello P. (2012), Lausanne, in preparation, philippe.lo-bello@hepl.ch
- Millar R., Osborne J. (1998) *Beyond 2000, Science Education for the Future*, King's College, London.
- Rocard M. et al. (2007) *Science education now. A renewed pedagogy for the future of Europe*, Report to the European Commission.
- Royal Society (2010) *Primary science and mathematics education: getting the basics right*, London.
- Sánchez Sorondo M., Malinvaud E., Léna P., Ed. (2007) *Globalisation and Education*, de Gruyter.
- Serres M. (2011) *La Guerre mondiale*, Le Pommier, Paris.
- Unesco (2010) *Global Challenges in Science Education*, Unesco, Paris
- Weisskopf, V.F. (1960). “The visual appearance of rapidly moving objects”. *Physics Today* 13, 24.