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Erasmus Lecture 2005
From science to education: the need for a revolution

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Primary education for all seems on the way to being achieved throughout the world within a couple of decades, despite the deep inequalities and lack of resources that remain. Science education at an elementary level, during the first years of school, should now be considered as essential to the cultural, civic, ethical, economic and technical development of humans and societies, in a context of globalization, as the triad 'reading–writing–arithmetic' has been during the two last centuries. Yet current education practice – which often characterizes science lessons in developed countries as well as in developing ones, when they exist at all – is quite unsatisfactory, as it is more concerned with transferring knowledge of facts than with scientific literacy, and misses the goal of capacity building. New developments in the last decade, based on inquiry pedagogy and often proposed or led by science Academies, have demonstrated another way to communicate science, and to involve and train teachers. In France, the United States and Sweden, but also in China, Brazil and Egypt, the results of this new approach have led to great hopes for transformation, fully supported by science academies. In Europe, a recently implemented EU programme aims at similar goals, in the spirit of the Lisbon objectives toward a society of knowledge.

Introduction

A decrease of interest in science careers in developed countries, and in the role of innovation for the economic and military ambitions of nations, along with the growing questioning by the public to the perspectives offered by discoveries and technologies, are serious issues that are debated today inside and outside the scientific community. Given this, it seems reasonable to wonder if, throughout the

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world, the education systems are properly reacting and transmitting these new treasures of knowledge?

How are children of the world, in their years of compulsory education, prepared to cope, as future citizens, with these changes? If the generalization of learning and writing ability has been the goal of basic education for two centuries, is it not timely to consider an equally urgent, and new, goal regarding science education? Have the conceptual revolutions, introduced by Einstein in 1905 and the science of the 20th century, not modified the visions of our world beyond a small circle of intellectuals? Can these visions be shared to become a *common good* for the whole of humanity, or at least an increasingly large fraction of it? As a recent UNESCO report questions, is 'Science education in danger?'[1]

As an astrophysicist, I have devoted most of my professional life to a discipline that has experienced, in the last half-century, an incredible wealth of discoveries and new perspectives on our universe, its diversity and its evolution. These have largely been as the result of technological advances, including such things as CCD (Charge Coupled Device) cameras. I have also witnessed the fascination these discoveries exert on young people, at the same time as creationism or astrology flourish in some of the most developed countries, and well-educated youngsters believe seasons are caused by changes in the distance from the Earth to the Sun! Having been involved, for ten years, in science education issues throughout the world and cooperating with many science academies on the subject, I feel a sense of urgency, which I wish to share.

Beginning with some reflections on Einstein, I will consider basic education throughout the world, and the place science holds within it, and then the arguments for introducing science education as a new essential component of basic education. A number of actions, undertaken in many countries, which have taken the challenge, do seem rather successful and have taught us many lessons. The possible role of Europe will indeed be especially underlined, for its own development but also for the role it could play in the world.

Some lessons from Einstein

In 1905, the young Albert Einstein published three articles[2] that revolutionized physics – the very same physics that Lord Kelvin had, a few years earlier, considered as definitely concluded by the electromagnetism of James Maxwell and the thermodynamics of Ludwig Boltzmann. Indeed, these articles introduced entirely new ideas in physics and opened immensely fertile or radically questionable avenues (such as the Hiroshima bomb) for the whole century. These ideas have deeply modified our representations of some fundamental elements of nature, which anyone, whether physicist or not, encounters when using such common words as matter, energy, light, space, time, universe. Let me simply give two examples.

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The first paper[3] of 1905 deals with the creation and conversion of light. Light quanta were mere abstractions when Max Planck introduced them for the first time in 1900. In his paper, Einstein questioned the commonly accepted view that the energy of a light ray can be distributed continuously over an ever-increasing volume and showed the need to quantify the exchanges of energy between light and matter. The quantum world led to many objects of our daily life – lasers, digital cameras – as well as to the understanding of the light emitted by stars. Yet, very few people have absorbed this quantum representation of the micro-world – even physicists, many of them using it from a purely technical point of view. It is so far from common sense and experience that it seems simply beyond understanding, as illustrated by the famous example of the Schrödinger cat, which could be considered simultaneously dead and alive!

Gravitation is a universal property of nature, which determines the structure of the universe. After the introduction of Special relativity in 1905, the conceptual revolution that came with the Einstein's 1916 article[4] totally changed our representation of the good old force attracting the Earth to the Sun, by proposing a coupling between space, time and the presence of mass. Space could even become closed on itself when matter is sufficiently concentrated – this concentration being defined by a simple relation,[5] which set the science of the black hole. Today, astronomers have found massive black holes, as in the centre of our galaxy,[6] within which the physical state of matter or the progress of time remain a deep mystery. Relativistic corrections, accounting for the effect the Earth's gravitation imposes on time measured by clocks, are essential to ensure the accuracy of the clocks used in the Global Positioning Systems (GPSs) that some of us have in our cars.

Therefore, we observe a kind of contradiction between the omnipresence of these discoveries and the difficulty in understanding and sharing the new vision of nature they contain. Science curricula seem unable to convey anything but the 'old' physics, and its associated, outdated representations.

The legacy of Einstein sets clear goals for science education, since he so often stated, in various forms, the need to preserve and develop curiosity: 'The important thing is to keep questioning. Curiosity has its own reason for existing. One cannot help but be in awe when [man] contemplates the mysteries of eternity, of life, of the marvelous structure of reality. It is enough if one tries merely to comprehend a little of this mystery every day. Never lose a holy curiosity.' Or this other one: ' Ich habe keine besonder Begabung, sonder bin nur leidenschaftlich neugierig.' To develop freedom of thought, a critical mind, to never stop observing and thinking what nature offers to our thoughts, to avoid repeating previous knowledge and to be creative, are necessary conditions for discovery in science, and for invention in technology.

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However, one should not forget one important aspect in this legacy: the fact that these new powers given by science imply new responsibilities,[7] which is clearly spelled out in Einstein's heritage and life. Science education must also convey ethical values, an entirely new challenge if one wishes to implement it early, in primary or secondary education. The French philosopher Paul Ricoeur, reflecting about science and culture,[8] proposed:

> … une réponse de conciliation et de pacification à la question posée par le statut de l'homme dans le champ du savoir […] Il n'est pas sûr que les techniques et le politique puissent être caractérisés, comme la science, par un projet instaurateur, cette notion ne paraissant pouvoir s'appliquer qu'à l'*epistémé* comme projet de vérité […] Le faisceau des pratiques relatives aux mœurs garde une consistance propre dans le tableau de la pluralité des pratiques […] L'idée de justice en constitue l'emblème par excellence.

Ricoeur underlines the search for truth carried by science, while a human needs to refer to the notion of justice when acting.

Science in basic education, an overview

In 1881, soon after the proclamation of the Third Republic, primary education became mandatory in France, and immediately included science, under the name *Leçons de choses* (Object lessons). The proclamation of democracy, the transformations introduced by the industrial revolution, the needs for new qualifications led to the opening of the classroom to the discoveries of Arago, Watt, Faraday, Edison, Pasteur. Fighting against superstitions, asking children to join progress, based on an intimate contact with nature and manufactured objects, these object lessons had an immediate and utilitarian objective. Object lessons are nothing but an accumulation of relevant observations. Their repetition progressively hammers into the child's memory the empirical material from which may emerge the clear perception of a cause–effect relationship.[9] Object lessons were extremely successful in France, as well as in the United States and in the United Kingdom, although the First World War led to their progressive abandonment,[10] and to the current situation.

Since the Second World War and throughout the world, the goal has been to establish a universal access to primary education – aiming at the abilities to read, write and count – and great progress has been achieved. Primary education for all[11] was set by UNESCO members in 1990 as a target for 2015, but today's estimate considers that this goal will only be reached by 87% at that date. In 2001, 103.5 million children had no primary education at all and the world counts over 800 million unable to read. Continuing in school after the fifth year remains less than 75% of the eligible students in 30 countries (of the 91 for which data are available), while it is less than 66% in sub-Saharan Africa. Girls are particularly

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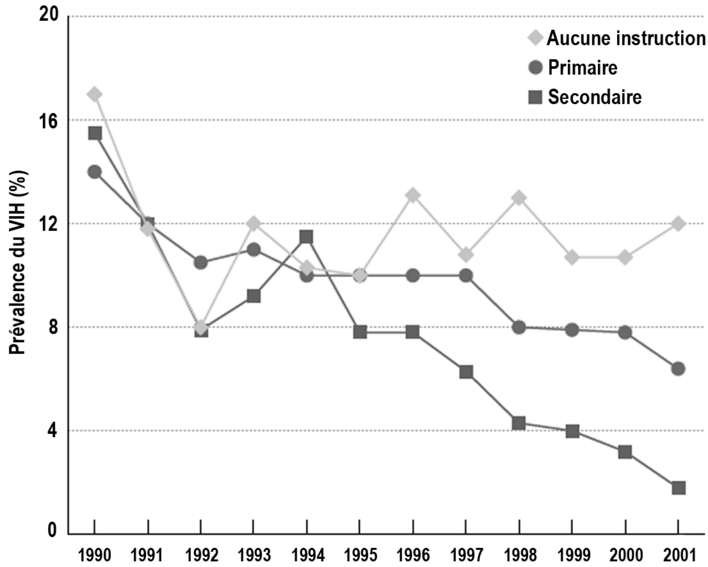

Figure 1. Prevalence of HIV in rural areas of Uganda, in percent, with respect to the instruction level, 1990–2001 (persons aged from 18 to 29). Source: Unesco, *Education for all*, 2004.

involved by this drop-out-of-school. In the global process of urbanization, a solid primary education is more than ever indispensable baggage. Let us recall the words of the French ethnologist Germaine Tillon who, in the 1950s, wrote about the process of *clochardisation* in Algeria (i.e. before the rebellion and independence war): '… a process which corresponds to a transition, without a shield, from the condition of peasant (the natural one) to the one of city dweller (i.e. modern). I call a "shield", a primary education leading to a qualification'.[12] Primary education also impacts on health behaviour, as recently demonstrated in Uganda for HIV prevention (Figure 1).

Scientific literacy

Considering that the fundamental triad of 'reading–writing–arithmetic', although not fully achieved yet throughout the world, is nevertheless close to being universal, the next step should be the introduction of science, taught in a proper manner, in modern primary education and to the end of basic compulsory education. This new literacy should become a new but essential part of education of the children of today. All children should properly be exposed, for the following reasons.[13]

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The virtues of science education

Science opens young people's minds to the wonders of the natural world; introduces them to the elegance and honesty of scientific endeavours; and equips them with cognitive and problem-solving tools that will serve them well in the future. Science brings children closer to the natural objects and the phenomena that surround them. It endows them with a rich understanding of our complex world, helps them practice an intelligent approach to dealing with the environment and develops their creativity and critical mind, their understanding of reality, compared to virtuality and teaches them the techniques and tools that societies have used to improve the human condition. As children become familiar with the universality of the laws of science, they also learn to recognize science's ability to create and cement together a unity for humanity. Science helps children – the future citizens – to develop imagination, humility, rigour, curiosity, freedom and tolerance – all essential ingredients for peace and democracy.

It would indeed be excessive to think that a good science understanding could alone lead to a world full of justice – historical examples show that highly developed countries, with an outstanding scientific capability, have behaved in a totally opposite way. As expressed above by Paul Ricoeur, science by itself cannot establish the grounds for ethical and moral behaviour, but it can greatly contribute to them.

Capacity building

These ideas of scientific literacy, of capacity building, are now discussed in many situations, and reach at least a consensus within the scientific community, if not yet in public policies. Let me quote here two definitions given by the OECD, within its PISA programme,[14] which aims at the evaluation of students at the age of 15. Scientific literacy is the 'capacity to use scientific knowledge, to identify questions and draw conclusions resting on evidence, in order to understand the natural world and to be more able to take decisions related to it, or to the changes it undergoes as a consequence of human activities.' The problem solving capacity of a person is '[the ability] to use cognitive process to compare and solve transdisciplinary situations, for which the solving path is not obvious, and where the knowledge which might be required does not exclusively belong to a unique domain of mathematics, science or reading.' These goals, which everyone will agree to consider vital for individual human development, argue for an integration of science into a broader frame, beyond the traditional borders of disciplines in which today most of education and of teacher training is organized.

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Science in elementary schools

What is, then, the current status of science education at elementary levels (until the ages of 13–14)? When children, age 10, were asked to 'please, draw a scientist', a systematic study of such representations,[15] such drawings show only men, these are always alone, they are ugly, threatening or devil-like, and are surrounded by various symbols that all express the comment written by one child: 'Scientists are often inscrutable and impossible to understand'. One should then not be surprised by the judgements that the ROSE study[16] has carefully measured on a large scale: teenagers – age 15 – who, in the majority, do not rate science high in their preferred subjects, and do not like to imagine their future professional activity as 'working with machines and tools', preferring 'to work with people'. Equally, girls reject much more science than boys. There is a strong and systematic difference between developing countries and developed ones, the teenagers from the former always rate science and technology higher, with less differences between boys and girls.

Returning to the drawings test, one observes that, when the reality of the nature, practice, and actors of science is better perceived by students, after a few months of exposure to an improved education, the drawings changed completely, the scientists are now handsome men, women, or children, and simple instruments or phenomena, and positive comments appear. In the PISA studies[17] on the science performance of 15 year old students, it is no surprise to observe the relatively poor performance of developed countries, such as France or Germany, the low performance of many developing ones, and the very large scatter of results for practically all countries.

Teachers and science

We have identified some symptoms that are the causes of the illness? Why has science become so difficult to communicate in primary education? Is it due to the nature of science, to the scientists themselves, the teachers or the available resources? Understanding and possibly curing this, is a real challenge. In primary schools of most countries, there is a single, polyvalent teacher, who usually loves children, is trained in educational matters, and may have had some specialized training in a particular discipline, but rarely in science. Teachers perform well in language education, but poorly in science education – if they practice it at all. On the other hand, they fear the complexity of science, the handling of experiments in the classroom, children's questions they would not be able to answer properly and the competition with television. Often, their understanding of the nature of science is poor or inadequate: scientific reasoning, the role of observation, experiments and hypothesis is unclear to them; the status of true or false, probable or uncertain statements is fuzzy. They lack a vision of the unity of science, of the

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relationship between science and technology, beyond the borders of disciplines (physics, biology, etc) they have been taught themselves in high school. In addition, the distance of these teachers from the scientific community is immense: what they know of it is what appears in the media, which present brilliant scientists and 'extreme science' (e.g. complex machines, the microscopic world) rather than the science-of-daily-life, which is most appropriate to elementary teaching. Conversely, active scientists and scientific institutions often consider that the elementary character of this early and supposedly easy science does not deserve their attention.

Universality and diversity

If science is to be universal, child development must be deeply rooted in the culture of the family, society and the environment. Science teaching must simultaneously convey universality but respect diversity, in order for its content to make sense to the child. This is not so easy, especially when traditions or religions are encountered in frontal collisions. Facing the simple question asked by a chinese child 'Why should I wash my hands?', will the teacher lead the child to understand the existence of bacteria? Or to accept the existence of good or bad breath? Two worlds of representations – indeed equally respectable – may collide in the child's mind, or in the parent's vision of science. Teaching of science is, in this context, a *vertical* one, i.e. transmitting knowledge, learned by heart and sometimes poorly understood by the children, with little or no space for active investigation, rather than helping to discover answers to real questions.

New visions and actions

Since 1998, in less than a decade and worldwide, an impressive number of international conferences[18] have questioned early science education, either at primary level or within the (usually nine) years of compulsory schooling. Even more remarkable, most of them were arranged by science academies[19] or organizations of scientists, but not by Education Ministries. They all addressed, in various forms, this new challenge of preparing the youth to live in a century where science and technology are expected to be omnipresent in society, necessary for a sustainable development and to raise inescapable ethical questions. They have progressively established a new pedagogical model, made explicit its principles and disseminated it by a number of local successful innovations.

Principles

Under the generic designation of *Inquiry* teaching and with the explicit support of science academies, scientists in Brazil (*Mao na massa*), Chile, China (*Zuo zhong xue* or *Learning by doing*), France (*La main à la pâte*), Mexico, Sweden,

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Switzerland (*Penser avec les mains*), the United States and many others have begun to implement this kind of teaching at various scales, indeed in collaboration with the education authorities. Based on the curiosity of children at an early age, it essentially focuses on the science of nature, and the associated technologies, without introducing at this stage too much distinction between disciplines – physics, chemistry, astronomy, biology, etc. The relationship with mathematics is more or less developed in each programme, but did not at first appear as urgent as with language learning (oral and written). In any case, mathematics, included in the triad *reading–writing–arithmetic*, seems to suffer less than natural sciences in primary schools.

The InterAcademy Panel, which federates 90 science Academies worldwide, has summarized the *Inquiry* principles as follows:[20]

A. Teaching of the sciences to both girls and boys should begin in their primary and nursery schools. There is evidence that children, from the youngest age, are capable of building upon their natural and insatiable curiosity to develop logical and rational thought. This is supported by modern development in cognitive sciences, tying the emotions of early learning to the perception of the natural world.
B. Teaching should be closely tied to the realities with which the children are confronted locally, in their natural environment and their culture, in order to facilitate continuing exchange with their family and friends.
C. Teaching should be based, to a large extent, upon models of inquiry-based pedagogy, assigning a major role to questioning by the students, leading them to develop hypotheses relating to the initial questions and, when possible, encouraging experimentation which, while simple in terms of the apparatus used, can be performed by children themselves.
D. In this manner one should avoid, as far as possible, a teaching of the sciences which is handed down vertically by a teacher enunciating facts to be learnt by heart, in favour of one where the acquisition of knowledge is horizontal, that is, which directly connects children with nature – inert or living – at the same time involving their senses and their intelligence.

How people learn[21]

Cognitive sciences have made great progress in the last few decades, and the understanding of the learning processes in the first ten years of life is progressing, helped by the new investigation tools that brain research offers nowadays. The

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impact of this progress begins to be felt on educational issues[22] such as reading abilities and dyslexia, numeracy, language learning, and one may soon expect to have new insights on this golden age of curiosity – 4 to 12 years – where children are full of questions about the natural world and its phenomena – the constant curiosity and very questions from which it is easy to build an inquiry-based teaching of science. After the work of Howard Gardner, the diversity of intelligence is now accepted, and the classical science education, giving an excessive role to abstract knowledge, finds a solid theoretical basis in experimental psychology to evolve. Similarly, the recently demonstrated importance of emotions in the learning process, especially during this first decade of life, provides a new framework[23] in which to rethink the way science is taught. We seem to observe today what Condorcet stated in a prophetic manner:[24] 'The progress of sciences ensures the progress of the art of teaching which, itself accelerates the progress of sciences'. Yet, these findings are far from being known by teachers or introduced into their training.

La main à la pâte *in France*

As an example, I present here some aspects of a large-scale action carried out in France since 1996, which has proven to be very effective. This action is extensively described in a book, titled *L'Enfant et la science. L'aventure de La main à la pâte*.[25] In 1995, the Nobel prize winner, Georges Charpak was impressed by the example of his colleague Leon Lederman in Chicago, where deprived primary schools and high drop-out rates in downtown ghettos had led Lederman to launch a programme based on a new, inquiry-based science education. Along these lines, an action was proposed by Charpak in France, where science education had practically disappeared from elementary school education (which lasts five years). The *Académie des sciences* fully supported it, along with the Ministry of Education.

It soon appeared that the main obstacle lay first in the relationship of teachers with science[26] itself, then with a vertical method of teaching where questioning and experimenting were not considered essential. Many actions were implemented to counteract progressively these negative factors, the roots of which were mentioned above. Here are some milestones. In 1996 an experimental programme was started in 350 classes – a very small sample. To help and coach the teachers – a critical matter – an Internet site[27] was created, where resources for the class could be found, a permanent dialogue with voluntary scientists – acting as consultants – could be opened and exchanges of good practices between teachers encouraged. The attendance at this site grew considerably over the years, to reach over 200,000 connections per month in 2004, while there are about 320,000 primary school teachers in France. There were *Ten Principles* for the teachers.

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A strong emphasis was placed on the unity of science and technology– breaking with the disciplinary view many teachers inherited from their own training – as well as on the tight connection between science and language, with all teachers feeling the priority given to the latter subject by official instruction and parental pressure.

After an evaluation by the Ministry of Education, the virtues of the experimental programme were recognized and a nationwide implementation (2000–2003) was undertaken by the Ministry for the last three grades of elementary schools, providing teachers with new material for experimenting in the class and developing training sessions with the participation of scientists to modify the teacher's perception of science. In 2002, after a second evaluation, a new curriculum was published and put into force, explicitly referring to the *Inquiry* method and introducing science and technology from kindergarten onwards.

In parallel, the *Académie des sciences*, with the support of a great diversity of partners undertook to develop a set of 'pilot centres', in various areas and contexts – rural, urban, deprived or not – of the country, where innovative teaching could be developed and the results compared. The action *La main à la pâte* – the name under which this programme became popular – was supported by the media and the parents, and this demonstrated the interest of the society for an action that was aimed at reducing the gap between science and the citizens, at the very heart of education, i.e. in the primary schools themselves.

Ten years after the action began, the situation of science teaching in French schools has changed, both in quality (more *horizontal*, less *vertical* teaching) and in quantity: it is estimated that about 30% of the classes practice science with the basic ingredients of inquiry – an experiment notebook, experiments being carried in the class, while another 20% of teachers have engaged in some type of science teaching. *Classes maternelles*, ages 4 to 6, have been remarkably engaged in the process, exploiting their traditional and recognized quality in terms of active and interactive teaching.

While the in-service training sessions were in a very limited number and often little attended ten years before, they may represent, in 2006–2007, up to 10% of all possibilities offered to teachers. Some preliminary assessment studies have shown systematic positive effects such as improvement in language practice and learning, better integration of students belonging to cultural minorities in the classroom, the development of civic behaviour and the ability to debate.

It is clear that a persistent action in France, carried by the education authorities with the full support of the *Académie des sciences*, surviving successive political changes over a decade, has led to a profound transformation of early science education, which a currently planned evaluation process should help to analyse.

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In the coming years, it is hoped to pursue, in junior high schools, the effort of renewal, exploiting the aroused interest of these recent generations of children for science.

Inquiry throughout the world

During the same period, the movement expanded in many countries: *La main à la pâte* collaborates in 2005 with over 30 countries, under various forms, to develop inquiry-based education. The role of Academies and scientists has already been underlined, and its impact can be understood. Primary education, in many countries, focuses on the triad 'reading–writing–arithmetic', with little (vertical) or no science. Training of teachers is under the responsibility of 'Faculties of education', which have a strong focus on psychological or sociological visions of education, but almost no connection with the realm of hard sciences and its actors.

These actions lead to a number of conclusions, converging with the ones reached in France. Everywhere, no matter what the state of development, despite adverse conditions in teacher's training or salaries, there is an increasing perception of the need to add science education to the classical triad. The universality of science, which brings easily together scientists of various cultures, also allows exchanges of class protocols, teacher's difficulties and training methods. The Internet is providing an efficient tool for this dissemination of self-training of teachers: as an example, the French Internet site has been, or will soon be, replicated, or sometimes mirrored, in China (in Chinese), Egypt (in Arabic), in South-America (in Spanish and Portuguese) and Serbia (in Serbo-Croat). In addition, the Internet offers the possibility to create a distant coupling of classes on a joint project, such as repeating the Eratosthenes method for measuring the Earth's diameter using the shadow of a pole.[28]

Changing the vision of teachers

The most important aspect is the discovery, by many teachers and teacher's trainers, that science *can* (and preferably *must*) be taught in a horizontal way, contrary to what they previously believed. To achieve this, they must be coached and helped, and there the role of professional scientists and Academies becomes of prime importance, to stress the value of science education, to propose and implement a correct vision of the nature of science, of its unity beyond the various disciplines, of the reciprocal relationship between science and technology. Not least to install this vision in the depth of historical perspectives and cultural roots, and relate it to the other provinces[29] of culture and to convince education authorities to maintain the effort for a long period, since the characteristic time

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scales of educational changes, for matters of this complexity, are to be counted in decades rather than in years.

I cannot resist quoting here, almost *in extenso*, the letter I received from a young woman teaching in a primary school of Dalian (Liaoning Province, China), six months after a talk I had given on the subject in her city, before the beginning of her inquiry practice. She wrote:

> For a teacher, to say "I don't know" shakes all the traditional views on education. When I was a student, I never met a single teacher who would admit not to know. Teaching is a profession designed to transmit morals, give competencies, untie knots: no problem exists which could resist to a teacher. *I do not know* is a humiliation, no pupil will ever respect the teacher anymore […] Now [after practising inquiry-based teaching], I understand it differently. One can enjoy mountaineering without being an alpinist, or play music without being a professional. Even in the first year, there are difficult questions asked by the children, such as: "Why is tap water transparent? The sky dark at night? The hairs of my grandfather becoming white?" Not knowing the answer is normal. Certainly the teachers know more than their pupils, but this does not mean we know everything, neither that we always should show that we know […] We must be like art directors: the children search, we guide them, they find, and we share the joy of discovery. Superficially, to say *I don't know* seems easy, but in fact remains difficult, because we always remain influenced by the traditional vision of teaching. At the very end, it is experience that teaches the truth.

This testimony shows the profound changes that must be achieved in teacher's attitudes to implement inquiry learning. One key change deals with the method of their own training in science, either vocational or in-service. How could they teach inquiry if they never have practised it themselves? How could they see that science is first questioning, if all they encountered was transmitted through formal lectures or pre-formatted laboratory work? How could they perceive the unity of science if they never crossed the categories of disciplines? How could they appreciate the fragile and immense curiosity of children if they never experienced their own curiosity? Ultimately, how could they teach science if they had not, intimately albeit briefly, perceived its flavour, as they like to read a book or write an essay, even though knowing they would probably never become a professional writer?

Evaluation

Integrating science into the fundamentals of primary education is an objective we have tried to justify in detail, on the basis of the child's curiosity, the sharing of human culture, the universality of science, and many other aspects. We have given some example of positive results, and could give much more, if not limited by

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the length of this review. Yet, the inquiry-type of teaching, and its practical application, deserves evaluation, which ultimately would compare its actual results with the expected ones. As a matter of fact, it is often stated that such a proof, and if possible quantitative, is needed to proceed further. Yet, it will always be extremely difficult to provide a demonstration of the positive influence, on children's minds, of an early exposure to inquiry in science, as there are so many parameters involved, related to the family, the background, the teacher, the way the child's kind of intelligence is valued, etc. We have to rely, as in many choices made on education, on some intimate conviction and its sharing after as large a discussion as possible.

This being said, it is worth quoting here, as a remarkable example, the evaluation achieved by Michael Klentschy, superintendent in the district of El Centro, California. Helped by the Jerry Pine and his students from the California Institute of Technology, Klentschy has carried out since the mid-1990s an inquiry into learning in his district, which is almost entirely populated by Hispano-Americans (migrant workers). The study has been on those students, when, six years after leaving the elementary schools of El Centro, they apply for entrance to the University of California system. The average success rate of this selection is 12% of all students of California. Among them, the minority students (mostly Hispano-Americans) rate only 4%, and these numbers are quite stable. However, the inquiry-taught students from El Centro have reached the average level of California, providing a splendid demonstration of the *long-term* effects of early inquiry science, even in topics that are *not* directly related to science – as is indeed the case in this entrance selection. Inquiry builds capacities.

Aside from this spectacular result, it will be necessary, in the coming years, to elaborate evaluation tools that will be able to appreciate how: a critical mind, creativity, competency in front of unexpected situations, and ability to conceptualize and develop abstract thinking, are obtained by this pedagogy. This is indeed more difficult than measuring the orthographic competence, the knowledge of scientific facts or the practice of algorithms. The *InterAcademy Panel* is now establishing a network of partners to build such tools in order to evaluate inquiry teaching.

An ambition for Europe

As shown above, many countries throughout the world have collaborated with the pioneering ones. What about European countries, with all their bright scientific and cultural heritage? Reading the Declaration of Lisbon, proclaimed in 2000, it is clear that reaching the goal proposed there (the creation of a first-rank knowledge economy) will require a profound transformation of science education.

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Two specific facts must be mentioned: first, nowhere more than in Europe is the fracture apparent between the scientific and technical society on one hand, and the public (including a large fraction of elementary school teachers) on the other, as demonstrated in public debates, the media or in the science vision of youngsters. Second, among these youngsters, the interest in choosing a career in science or technology is constantly decreasing, to a point that is felt by governments as threatening to the economy. These two facts require a complete re-thinking of science presentation in schools, and especially at the age where children are most open, in their golden age of curiosity, i.e. in primary schools.

Europeans have remarkably succeeded in creating research organizations which, in a few decades, have reached the summit of competence and discovery, such as the CERN in Geneva, ESO in Garching, EMBL in Heidelberg, ESA in Paris and elsewhere, ESRF in Grenoble and many others. The virtue of these structures is that the definition of their programmes has been made by scientists in full independence, their permanence despite national fluctuations, their ability to mix the diversity of European talents in a creative way. As Georges Charpak often stated, why would Europeans not have the same capability of initiative and success when dealing with science education? It is true that, at the moment, education seems to be entirely left to the hands of nations, on the basis of the subsidiarity principle. The Project of European Treaty is going shyly beyond this, opening the door to 'actions of coordination or complement' (Art. III-282). The subsidiarity principle may indeed make sense for organizational matters, or curricula specificities that are deeply rooted in local culture, but it is not so clear it should apply when universality of science, and of children's curiosity, has already demonstrated that common concepts and resources can be applied, common action undertaken.

With these facts in mind, a new initiative has been taken by the *La main à la pâte* group in France, and partners in 11 other European countries (Figure 2), in order to create, from 2006 onward, a network of European cities (called *seed cities*), one per country, in which a set of primary schools – a set of modest size, i.e. about 100 classes – would after four years become prototypes of a fully renewed science teaching. The project, called *Pollen*, will aim at using the existing experience in France, the UK, Sweden and other countries, to help the less-advanced ones at establishing common services of data and resources exchange, evaluation concepts, teacher's training protocols and comparisons, with the goal to develop in each country a prototype that could become a model integrating all the specific aspects of education in this particular country, organizationally as well as culturally. In several of these countries, science Academies, as well as civic officials, have already agreed to join their effort with the educational authorities, in order to realize a new triad *school–society–science*

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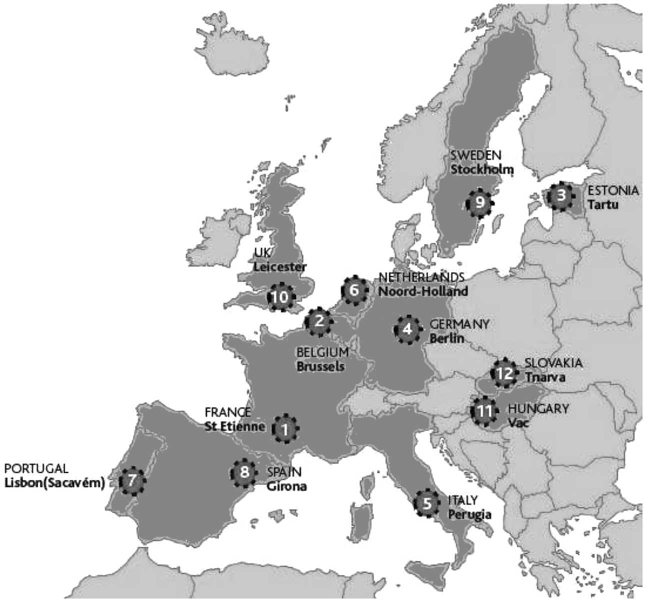

Figure 2. The *Pollen* seed cities in Europe, which will begin in 2006 to develop excellence prototype centres for science education in primary schools, supported by the European Commission. (Note: in the final Pollen design, Slovakia is replaced by Slovenia.)

community, which in many instances has already proven its efficiency to implement deep changes.

Conclusion

At the end of the 19th century, science seemed to contain all the promises of a bright future for humanity. One century later, our societies are full of doubt about their future, and the legitimate role science could play to shape it is unclear to many. What has remained fresh and always new is the treasure of curiosity in successive generations of children, but this curiosity, if not nurtured by education, soon disappears, leaving *blasé* youngsters and citizens unable to cope with the new space of freedom offered by the technological development.

This has to be modified at the heart of transmission between generations, i.e. within education. The needed transformation is deep and difficult but possible. It cannot happen, contrary to many reforms in education, without a deep involvement of the science community, if possible at the highest level. It requires time, patience and imagination. It can succeed because we have some small but successful models, because society and parents feel it is essential, because teachers are entirely prepared to start if they perceive they are not alone, and see concrete signs of help. Proposing a unified vision of knowledge, where science – including

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mathematics – is integrated with language, history, geography to answer the curiosity of children, develop their creativity and critical mind, must succeed since it is an urgent need of our times.

Europe has two challenges waiting for action: the first is to transform science education in primary and junior high schools. The second is, combining the universality of science and respect for cultures, to help the developing world to do the same. When we observe the current status of science education in so many countries, it is indeed a *revolution* that is proposed.

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26. Again, the term *science* is used in what follows to designate the sciences of nature (experimentation and observation). It does not mean that experimentation and observation should not be part of a good elementary teaching of mathematics.
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29. This definition of science as ‘a province of culture, and one of the most beautiful’ is due to Yves Quéré, from the French Académie des sciences, of which he is the former Foreign Secretary. He has developed this in several books: Y. Quéré (2002) *La science institutrice* (Paris: Odile Jacob); Y. Quéré (2005) *La sagesse du physicien*, L’œil neuf (Paris: Odile Jacob); Y. Quéré (2006) *Qu’est-ce que la culture?* (collective) (Paris: Odile Jacob), to be published.

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Pierre Léna is Emeritus Professor at the Université Denis-Diderot (Paris 7) and was Director of the Graduate School of Astrophysics. He has been instrumental in developing adaptive optics to enable large telescopes to reach their diffraction limit and also contributed to the Very Large Telescope built in Chile. Since 1996 he has joined George Charpak and Yves Quéré at the *Académie des Sciences* in the programme addressing the improvement of science education in schools.

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