From science to education : the need for a revolution

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Abstract. Primary education for all seems on the way to be achieved throughout the world within a couple of decades, despite the deep unequalities and lack of resources which remain. Science education at an elementary level, during the first years of school, should now be considered as essential to the cultural, civic, ethical, economical and technical development of humans and societies, in a context of globalisation, than the triad « reading-writing-counting » has been during the two last centuries. Yet, the current pedagogy which often caracterises the science lessons, in developed countries as well as in developing ones when they exist at all, is quite unsatisfactory, as it is more transferring knowledge of facts than 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, to involve and train teachers. In France, United-States or Sweden, but also in China, Brazil or Egypt, the results of this new approach lead to great hopes for transformations, fully supported by science Academies. In Europe, a recently implemented EU program aims at similar goals, in the spirit of the Lisbon objectifs toward a society of knowledge.

1. Introduction

Some decrease of interest for science careers in developed countries, the role of innovation for the economic and military ambitions of nations, and the growing questioning addressed by the public to the perspectives offered by discoveries and technologies are serious issues which today are debated inside and outside the science community. Given this fact, it seems reasonable to wonder if, throughout the world, the *education systems* are properly reacting and transmitting these new treasures of knowledge ?

How are children of the world, within their years of compulsory education, prepared to cope, as future citizens, with these changes ? If the generalisation of learning and writing ability has been the goal of basic education since two centuries, is'nt it 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, 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 humanity, or at least an increasingly large fraction of it ? As a recent UNESCO report questions it, is « Science education in danger ? »[1]

As an astrophysicist, I have indeed devoted most of my professional life to a disciplin which has experienced, in the last half-century, the incredible wealth of discoveries and new perspectives on our universe, its diversity, its evolution. These have largely been the result of technological advances, such as the CCD (*Charge Coupled Device)* cameras. I also witness the fascination these discoveries exert on young people, while at the same time creationism or astrology may flourish in some of the most developed countries, and well educated youngsters believe seasons are caused by the variable distance from Earth to Sun ! Having been involved, since 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 attempt here to share.

Beginning as appropriate, in this anniversary year of 2005, with some reflections on Einstein, I will then consider basic education throughout the world, and the place science holds within it. Next, the arguments to introduce science education as a new essential component of basic education are presented. To support this point, I describe a number of actions, undertaken since a decade or so in many countries, which have taken the challenge, do seem rather successfull and have taught us many lessons. The possible role of Europe, within the Union, will indeed be especially underlined, for its own development but also for the role it could play in the world. In conclusion, I will come back to my title and justify the word *revolution*.

2. Some lessons from Einstein

In 1905, the young Albert Einstein published three articles[2] which 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 (as the Hiroshima bomb) avenues 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 words as matter, energy, light, space, time, universe ? Let us simply give two examples.

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 questionned 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 opened to investigation, leading to the 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 integrated this quantum representation of the micro-world – even physicists, many of them using it from a purely technical point of view. It is so distant from common sense and experience that it seems simply beyond understanding, as illustrated by the famous example of the Schrödinger cat, being simultaneously dead and alive.

Let us consider now gravitation, this universal property of nature which determines the structure of the whole universe. After the introduction of the special relativity in 2005, the conceptual revolution came with the Einstein's 1916 article[4], which totally changed our representation of the good old force attaching the Earth to the Sun, by proposing a coupling between space, time and the presence of masses. Space could even become closed on itself when matter is sufficiently concentrated – this concentration being defined by a simple relation[5], which sets the horizon of a black hole. Today, astronomers discover massive black holes, as in the center of our Galaxy[6], within which the physical state of matter or the running of time remain a deep mystery. And relativistic corrections, accounting for the effect the Earth's gravitation imposes on the time measured by clocks, are essential to ensure the accuracy of the clocks used in the *Global Positioning System* (GPS), which we have in our cars to find directions.

Therefore, we observe a kind of contradiction between the omnipresence of these discoveries and the difficulty to understand and share the new vision of nature they contain. Science curricula, even at the end of secondary schools, 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 science to discover, and for technology to invent.

But one should not forget one important aspect in this legacy : the fact that these new powers given by science imply new responsabilities[7] is so clearly spelled in Einstein's heritage and life that there is no need to insist. Science education must also convey ethical values, a entirely new challenge if one wishes to implement it early, in primary or secondary education. The great 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. » In this text, Ricoeur underlines the search of truth carried by science, while a human, which indeed can be described by science, keeps also his specificity and has to refer to the notion of justice when acting.

3. Science in basic education, an overview

In 1881, soon after the proclamation of the IIIrd Republic, primary education became mandatory in France, and immediatly included science, under the name *Leçons de choses* (translated from the anglo-saxon « object lessons »). The proclamation of democracy, the transformations introduced by the industrial revolution, the needs for new qualifications led to open the classroom to the discoveries of Arago,Watt, Faraday, Edison, Pasteur. Fighting against superstitions, asking children to join the progress, based on an intimate contact with nature and fabricated objects, these *object lessons* had an immediate and utilitarian objective.

« Object lessons are nothing but an accumulation of relevant observations. Their repetition progressively hammers, in the child's memory, the empirical material from which may emerge the clear perception of a cause-to-effect relationship[9] ». Object lessons were extremely successfull in France, as well as in the United States and in the United Kingdom. The great slaughter of World War I, the drama which followed led to their progressive abandon[10], and to the current situation.

Since World War II and throughout the world, the goal has been to establish an universal access to primary education – aiming at the abilities to read, write, 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 evaluation considers that this goal shall only be reached at 87 % by this date. In 2001, 103.5 millions of children had no primary education at all and the world counts over 800 millions analphabets. Survival in school after the 5th year remains less than 75 % of the children in 30 countries (over the 91 for which data are available), while it is less than 66 % in sub-saharian Africa. Girls are first concerned by this drop-out-of-school. In the global process of urbanisation, a solid primary education is more than ever an indispensable baggage. Let us recall the words of the French ethnologist Germaine Tillon who in the 1950 wrote about the process of *clochardisation* in Algeria (i.e. before the rebellion and independence war of this country) : « …a process which corresponds to a transition, without shield, from the condition of peasant (the natural one) to the one of city dweller (i.e. modern). I call « shield » a primary education leading to a qualification[12] ». Primary education impacts also health behaviour, as recently demonstrated in Uganda for the VIH prevention (Fig. 1).

4. Scientific literacy

Considering that the fundamental triad of « reading-writing-counting », although not fully achieved yet throughout the world, is nevertheless close to be soon universal, the next step should be to introduce science, taught in a proper manner, in modern primary education, to be complemented until 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, extracted from Ref. [13].

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 phenomena that surround them; endows them with a rich understanding of our complex world; helps them practice an intelligent approach to dealing with the environment; develops their creativity and critical mind, their understanding of the resistance 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 the mental and moral predispositions to 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 are here to show that highly developed countries, with an outstanding scientific capability, have behaved totally at opposite. 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 instances, and reach at least a consensus within the scientific community, if not yet in public policies. Let us quote here two definitions given by the OECD, within its PISA program[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 *solving problem* 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, deeply plea for an integration of science into a broader frame, beyond the traditional borders of disciplins which today organize most of education and of teachers training. I shall describe below how these general principles have inspired the actions carried by Academies in the recent years.

Science in elementary schools. What is, then, the current status of science education at elementary levels (until the ages of 13-14) ? Fig. 2a reproduces what a child, age 10, made when he was asked « Please, draw a scientist ». A systematic study of such *a priori* representations has been undertaken[15], and they all converge, not only in France, but in many countries. The drawings show only men, these are always alone, they are ugly, threatening or devil-like, they are surrounded by various symbols which all express what says the comment written by the child : « Scientists are often closed and impossible to understand ». One should then not be surprised to observe on a large scale the judgements which the ROSE study[16] (*Relevance of science education*) has carefully measured : teen-agers – age 15 – who, in majority, do not rate science high in their preferred subjects, do not like either to imagine their future professional activity as a « work with machines and tools », prefering « to work with people » (Fig. 3). Equally consistent with the observations made on the drawings, girls reject much more science than boys. Finally, there is a strong and systematic difference between developing countries and developed ones, the teen-agers from the former always rate science and technology higher, with a fewer difference between boys and girls. Coming back 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 a rejuvenated science education, their drawings entirely changed (Fig. 2b) : handsome men and women, or children, simple instruments or phenomena, positive comments do appear.

Therefore, in the PISA studies[17] on science performance of 15 years old students, it is no surprise to observe the relatively poor performance of developed countries – as France or Germany –, the low performance of many developing ones, and the very large scatter of results for practically all countries (Fig. 4).

<u>Teachers and science.</u> We have identified some symptoms, which 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 themeselves, the teachers or the available resources ? Understanding this and possibly curing it, is a real challenge. In primary schools of most countries, there is a single, polyvalent teacher, very often a woman. She, or eventually he, usually loves children, is trained in educational matters, and had some specialized training in a particular disciplin, but rarely in science. Teachers perform well for language education, but poorly in science education – when 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 which they would not be able to answer properly, the competition with television. Often, their understanding of the nature of science is poor or inadequate : scientific reasoning, the role of observation, experiments, hypothesis is unclear for them ; the status of *true* or *false, probable*

or *uncertain* statements is fuzzy. They lack a vision of the unity of science, of the relationship between science and technology, beyond the borders of disciplins (physics, biology, etc.) they have been taught themselves in high school. In addition, the distance of these teachers with the scientific community is immense : what they know of it is carried by the media, who rather present bright scientists and « extreme science » (complex machines, 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 universal, the child development is deeply rooted in the culture of the family, the society, the environment. Science teaching must simultaneously convey the universality and respect the diversity, in order for its content to make sense for the child. This is not so easy, especially when traditions or religions encounter 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 (*qi*) ? Two worlds of representations – indeed equally respectable – may collide in the child's mind, or in the parent's vision of science…

As an unescapable consequence of all these factors, teaching of science, if any, is in this context a *vertical* one, 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.

5. New visions and actions

At the turn of the century, 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 called by science Academies[19] or organizations of scientists, but not by education ministries. They all adressed, 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 the society, necessary for a sustainable development and raising unescapable ethical questions. They have progressively established a new pedagogical model, made explicit its principles and above all disseminated a number of local successfull innovations.

Principles**.** Under the generic designation of *Inquiry* teaching and with 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, Switzerland (*Penser avec les mains*), United-States and many others began to implement this pedagogy at various scales in their country, indeed in collaboration with the education authorities. Based on curiosity of children at early age, it essentially focuses on science of nature, and the associated technology, without introducing at this stage too much distinction between disciplins – physics, chemistry, astronomy, biology, etc. The relationship with mathematics is more or less developed in each program, but did not at first appear as urgent as the one with language learning (oral and written). In any case, mathematics, included in the triad *reading-writing-counting*, seem to be less suffering than natural sciences in primary schools.

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

« A/ Teaching of the sciences to both girls and boys 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/ This 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/ This 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 decades, and the understanding of the learning processes in the first ten years of life is progressing, helped by the new investigation tools than brain research offers nowdays. The impact of these 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 on 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 intelligences is now an accepted fact, and the classical science education, giving an excessive role to abstract knowledge, has 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 frame[23] 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 progresses of the art of teaching which, themselves, accelerate then the progress of sciences ». Yet, these findings are far from being known by teachers, and 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 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 Georges Charpak was impressed by the example of his colleague and Nobel prize Leon Lederman in Chicago, where deprived primary schools and high drop-out rates in downtown ghettos had led Lederman to launch a program based on a renovated, inquiry-based science education. Along these lines, an action was proposed by G. Charpak in France, where science education had practically disappeared from elementary schools (which lasts five years). The Académie des sciences fully supported it, along with the ministry of education.

It soon appeared that the main obstacle laid first in the relationship of teachers with the science[26] itself, then with an horizontal method of teaching where questioning and experimenting were considered more essential than a vertical transfer of knowledge. Many actions were implemented (Fig. 5) to progressively counteract these negative factors, the roots of which having been mentionned above. To make a long story short and give some milestones : in 1996 an experimental program started in 350 classes, voluntarily a very small sample. To help and coach the teachers – the most critical point indeed –, an Internet site[27] was created, where resources for the class could be found, a permanent dialog with voluntary scientists, acting as consultants, could be opened, exchanges of good practices between teachers encouraged. The attendance of this site grew considerably over the years, to reach over 200 000 connections per month in 2004, while France counts about 320 000 primary school teachers. Principles of inquiry were enunciated in the simple shape of *Ten Principles* for the teachers. 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, all teachers feeling the priority given to the latter subject by official instructions and parents pressure.

After an evaluation by the ministry of education, the virtues of the experimental program were recognized and a nation-wide renovation (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, 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, explicitely referring to *Inquiry* method and introducing science and technology from kindergarten onwards.

In parallel, the Académie des sciences, with a great diversity of partners supporting the action, undertook to develop a set of « pilot centers », in various areas and contexts – rural, urban, deprived or not – of the country, where innovative teaching could be developed and its results mutualised. The action *La main à la pâte* – this is the name under which this program became popular – was supported by the media and the parents, this demonstrated the interest of the society for an action which aimed at reducing the fracture between science and the citizens, at the very heart of education, i.e. in the primary school 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 the teachers have engaged in some type of science teaching. Kindergarten (called *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 unattended ten years before, they may represent in 2006-2007 up to 10 % of all possibilities offered to teachers. Some preliminary assessement 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, development of civic behaviour and ability to debate.

To conclude, 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 cycles over a decade, has led to a profound transformation of early science education, which a currently planned evaluation process should help to analyse. In the coming years, it is hoped to pursue in the junior high school the effort of renovation, 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 thirty 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. As a matter of fact, primary education is in many countries focuses on the triad reading-writing-counting, with little (vertical) or no science. Training of teachers is under the responsability of « Faculty 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 is the state of development, despite adverse conditions in teacher’s training or salaries, there is an increasing perception of the need to include science education into the classical triad. The universality of science, which brings easily together scientists of various cultures, allows also exchanges of class protocols, teacher's difficulties and training methods. Internet is providing an efficient tool for this dissemination of self-training of teachers : as an example, the French Internet site has been or is replicated, or sometimes mirrored, in China (in Chinese), Egypt (in Arabic), in South-America (in Spanish and Portuguese) and Serbia (in Serbo-croatian). In addition, Internet offers the possibility to create distant coupling of classes on a joint project, such as repeating the Eratosthenes method for measuring the Earth diameter using the shadow of a pole[28].

Changing the vision of teachers. But the most important aspect is the discovery, by many teachers and teacher's trainers, that science *can* (and preferably *must*) be taught in an 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 disciplins, of the reciprocal relationship between science and technology ; to install this vision in the depth of historical perspectives and cultural roots, and relate it to the other provinces[29] of culture ; to propose convincing arguments to education authorities and maintain the effort for a long period, since the characteristic time 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 do'nt 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. Teacher 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 practicing 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 the faucet's water transparent ? The sky dark at night ? The hairs of my grand-father 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 do'nt 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 beautiful testimony shows the profound changes which 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 practiced it themselves ? How could they see that science is first questioning, if all they encounterd of it 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 disciplins ? How could they appreciate the fragile and immense curiosity of children if they never experienced their own ? Ultimately, how could they teach science if they had not, intimately albeit briefly, perceived its flavor, as they like to read a book or write an essay, even knowing they would probably never become a professional writer ?

<u>Evaluation.</u> 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 the length of this review. Yet, the inquiry pedagogy, and its practical application, deserve some kind of evaluation, which ultimately would compare its actual results with the expected ones. As a matter of fact, it is often stated that such proof, if possible quantitative, is needed to proceed further. Indeed, one has to comply with such requests. Yet, it will always be extemely difficult to provide a « demonstration » of the positive influence, on children's mind, of an early exposure to inquiry in science, as there are so many parameters in the result of a pedagogy, 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 an argumented discussion as large 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 renowned scientist Jerry Pine and his students from the California Institute of technology, Klentschy has implemented since the mid-1990s inquiry learning in his district, which is almost entirely populated by hispano-americans (migrant workers). A study has been carried (Fig. 6) on the students, when, six years after leaving the elementary schools of El Centro, they apply to the entrance selection of the University of California system. The Californian average of success to this selection is 12 % of all students. Among them, the minority students (mostly hispano-americans) only rate 4 %, and these numbers are quite stable. Fig. 6 shows how the inquiry-taught students from El Centro have rated : they reach the average level of California, providing a splendid demonstration of the *long-term* effects of early inquiry science, even in subjects which are *not* directly related to science – as it is 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 which will be able to appreciate how critical mind, creativity, competency in front of unexpected situations, abiitly 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.

6. An ambition for Europe

As shown above, many countries throughout the world have collaborated with the pioneering ones. What about Europan countries, with all their bright scientific and cultural heritage ? Reading the Declaration of Lisbon proclamed 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. Two specific facts must be mentioned : first, nowhere more than in Europe appears today a fracture between the « scientific and technical society » on one hand, the public (including a large fraction of elementary school teachers) on the other, as demonstrated in public debates, media or … in the science vision of youngsters (Figs. 2 and 4). Second, among these youngsters, the interest for choosing a carrier in science or technology is constantly decreasing, to a point which is felt by governments as threatening for 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 competeence and discovery, such as the CERN in Geneva, ESO in Garching, EMBL in Heildelberg, ESA in Paris and elsewhere, ESRF in Grenoble and many others. The virtue of these structures is the definition of their program made by scientists in full independence, their permanence despite national fluctuations, their ability to mix in a creative way the diversity of European talents. As the Nobel prize winner (physics, 1992) Georges Charpak often stated, why would not Europeans 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 of complement » (Art. III-282). The subsidiarity principle may indeed make sense for organisational matters, or curricula specificities which are deeply rooted in local culture, but it is not so clear it should apply when universality of science, and of children curiosity, has already demonstrated that common concepts and resources can be applied.

With these facts in mind, a new initiative has been taken by the *La main à la pâte* group in France, and partners in eleven other European countries (Fig. 7), 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 renovated science teaching. The project, called *Pollen*, will aim at using the existing experience – in France, 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 which could become a model integrating all the specific aspects of education in this particular country, organisationaly as well as culturally. In several of these countries, science Academies, as well as City officers, have already agreed to join their effort to the ones of educational authorities, in order to realise a new triad *school-society-science community*, which in many instances has already proven its efficiency to implement deep changes.

7. Conclusion

At the end of the XIXth century, science seemed to contain all the promises of a bright future for humanity. One century later, our societies are full of doubt on their future, and the legitimate role science could play to shape itis unclear to many. What has remained fresh and always anew 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 spaces of freedom offered by the technogical development.

This has to be modified at the heart of transmission between generations, i.e. within the education. I hope to have demonstrated that the needed transformation is deep, difficult but possible. It can not happen, contrary to many reforms in education, without a deep involvement of the science community, if possible at the highest level, i.e. Academies. It requires time, patience and imagination. It can succeed because we have some small but successfull models, because the society and the 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 mathematics – is integrated with language, history, geography to answer the children curiosity, 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 one is to renovate science education in the primary and junior high schools of European countries. The second is, combining universality of science and respect for the 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* which is proposed.

Figure 2.1: Prévalence du VIH dans les zones rurales de l'Ouganda (%), par niveau d'instruction, 1990-2001
(personnes âgées de 18 à 29 ans)

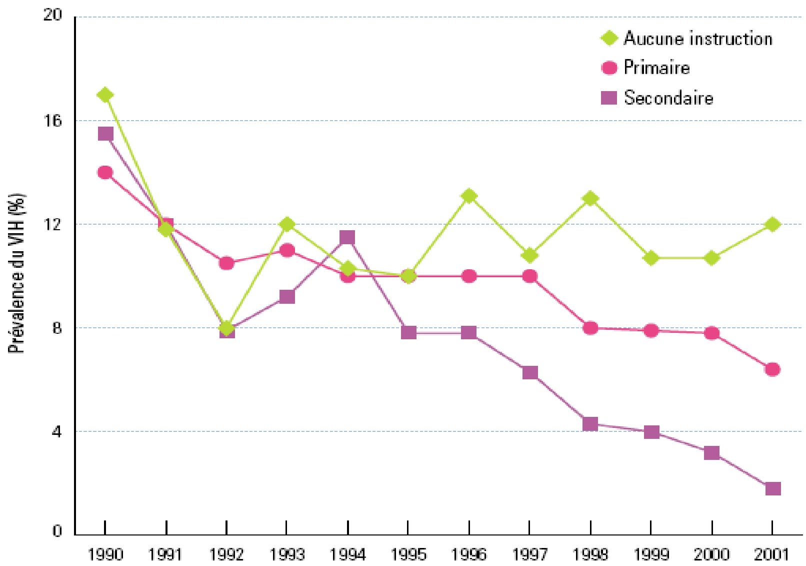


Fig. 1. Prevalence of VIH in rural areas of Uganda, in percent, with respect to the instruction level, 1990-2001 (persons aged from 18 to 29). Source : Unesco, *Education for all*, 2004.

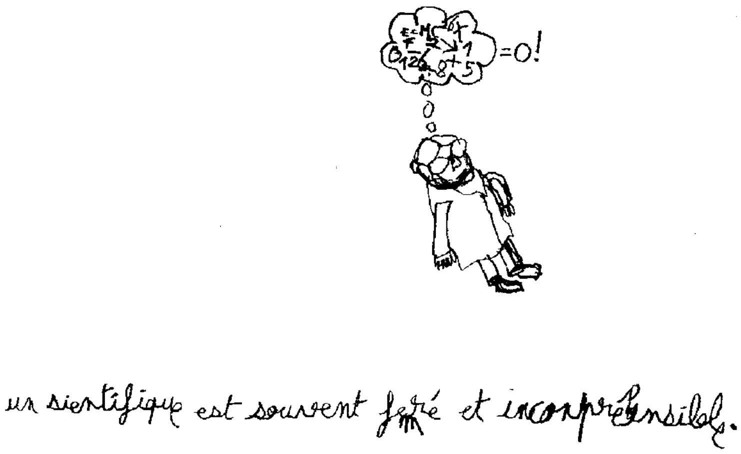


Figure 2a. Spontaneaou drawing of a child when asked to draw and define a scientist. The comment reads : « A scientist is often closed and impossible to understand ».(Courtesy of F. Liska & M.-O. Lafosse-Marin, Paris, 2004).

Figure 2b. Drawings of children after several months of Inquiry-based science teaching. (Source : ibid.)

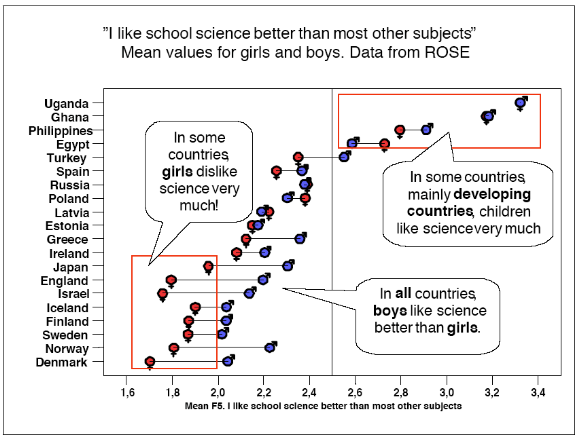
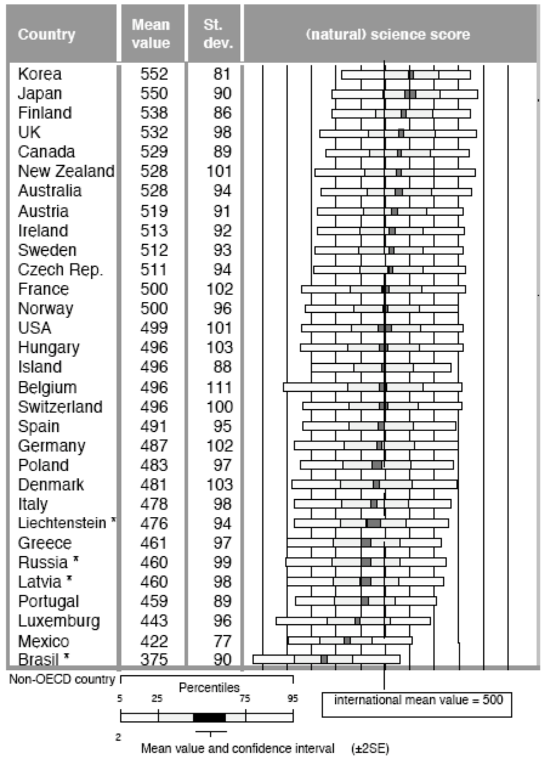


Figure 3. Answer of teen-agers (age 15) to the above-mentionned statement. From the ROSE enquiry, quoted in *Europe needs more scientists*, Report to the European Commission, presented by M. Gago, 2004.



Source : OECD Pisa database, 2001. Table 3.3

Figure 4. Performances of teen-agers (age 15) in science. PISA, OCDE, 2001.

Figure 5. Schematic descriptions of the main characteristics of the *La main à la pâte* program in France.

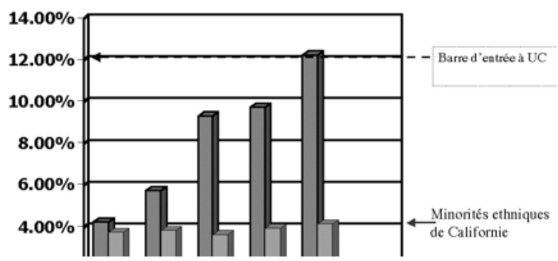


Figure 56. Score of El Centro hispano-americans young students, at the entrance selection of the University of California system, for the years 2000 to 2004 (in heavy gray). This increasingly progressing score has to be compared to the average score of all Californian students (12 %) and to the average score of all ethnic minorities of California (about 4 %). The increase of performance follows closely, six years after leaving the primary school, the amount of inquiry-based teaching these students have received. After Michael Klentschy, 2005.

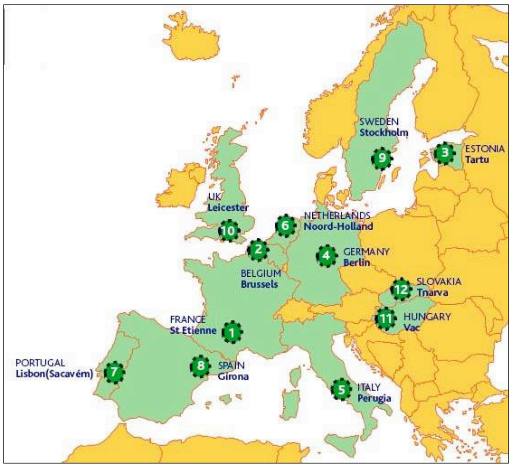


Figure 7. The *Pollen* seed cities in Europe, which will begin in 2006 to develop excellence prototype centers for science education in primary schools, supported by the European Commission.

[1] *Science education in danger*, Newsletter of Unesco Education Sector, N°11, Oct-dec 2004.
[2] The browian motion : (1905) *Ann.Phys*. XVII, 549-560 ; the quanta of light : « On a heuristic point of view about the creation and conversion of light », (1905) *Ann.Physik* XVII, 132, 1905 ; the special relativity : « Zur Elektrodynamik bewegter Körper » (1905) *Ann.Phys.* XVII, 891-921.
[3] « On a heuristic point of view about the creation and conversion of light », *Ann.Physik* **17**, 132, 1905.
[4] « Die Grundlagen der allgemeinen Relativitäts Theorie », *Ann.Physik* **49**, 769-822, 1916.
[5] The Schwarzschild horizon, or radius of a black hole of mass M is given by the expression $R = 2\ GM/c^2$, where G is the Newton constant of gravitation.
[6] « A star in a 15.2-year orbit around the supermassive black hole at the centre of the Milky Way », (2002) Schödel, R., Ott, T., Genzel, R., Hofmann, R., Lehnert, M., Eckart, A., Mouawad, N., Alexander, T., Reid, M.J., Lenzen, R., Hartung, M., Lacombe, F., Rouan, D., Gendron, E., Rousset, G., Lagrange, A.-M., Brandner, W., Ageorges, N., Lidman, C., Moorwood, A.F.M., Spyromillo, J., Hubin, N., & Menten, K.M.*Nature* 419, 694.
[7] R. R. Ernst, « The responsability of scientists, a European View », *Angew.Chem.Int.Ed.,* **42**, 4434-4439, 2003.
[8] Ricoeur, P. in *The cultural values of science* , Pontifical Academy of Sciences, Vol. 105, 2004.
[9] Hébrard, J. in *La main à la pâte. Les sciences à l'école primaire*, Flammarion, Paris, 1996.
[10] *Les sciences à l'école, quelle histoire !* An exhibit realized by the Académie des sciences in France, and its partners, to describe and analyze science education in primary schools since 1830 in France. This exhibit circulate in teacher's training institutes (IUFM) since 2004, as well as outside France.
[11] *Education for All*, A summary (2005), Unesco.
[12] Tillon, G. quoted in Lacouture, J., *Le témoignage est un combat*, Seuil, Paris, 2000.
[13] An InterAcademy Panel (IAP) *Statement on Science Education of Children* , Mexico City, Dec 2003.
[14] Program for International Students Assessment (PISA), OCDE, Paris.
[15] Study carried by Marie-Odile Lafosse-Marin, PhD in preparation, Paris, 2005.
[16] Relevance of Science Education (ROSE), quoted in the Report *Europe needs more scientists*, prepared under the direction of Mariano Gago, European Commission, 2004.
[17] PISA has carried evaluations in 2000 and 2003, and a new one is planned for 2006. The first ones dealt only partly with science while focusing on language, then mathematics. The 2006 evaluation will focus on science.
[18] Here is a list of these Conferences or Workshops : Budapest (1998), Strasbourg (1998), Beijing, (2000), Monterrey (2001, 2003, 2005), Santiago-du-Chili (2003), Vatican (2001, 2005), Kuala Lumpur (2002), Rio (2002), Boston (2002), Mexico (2003), Dakar (2003), Lima (2003), Penang (Malaysia, 2004), Bielefeld (2004), Erice (Sicily, 2004 et 2005), Amsterdam (2005), Stockholm (2005), Zlatibor (Serbie, 2005), Corpus Christi (USA, 2005).
[19] Let mention here, among many, the National Academy of sciences (USA), the Académie des sciences (France), the Royal Swedish Academy of sciences (Sweden), the Academia Brasileira de Ciências… as well as the InterAcademy Panel (IAP), the InterAcademy Council (IAC) and the International Council of Science (ICSU).
[20] IAP Mexico city 2003

[21] *How people learn. Brain, mind experience and school.* (1999) J. D. Bransford, A.L. Brown, and R. R. Cocking, Editors, National Research Council, Washington D.C.

[22] *Understanding the brain. Towards a new learning science*, (2002), OCDE, Paris.

[23] Handsbrain Education, Research Center forLearning Science at Southeast University (Nanjing, Jiangsu Province, China).

[24] in *Esquisse d'un tableau historique des progrès de l'art humain*, 1795, Vrin, Paris, 1970.

[25] The French program of renovation of the primary school science education, and its achievements, are described in detail in a recent book, to be soon published also in English and Spanish : Charpak, G., Léna, P., Quéré, Y. *L'enfant et la Science. L'aventure de La main à la pâte*, Editions Odile Jacob, Paris, 2005.

[26] Again, the term *science* is used in what follows to designate the sciences of nature (experimentation and observation). It does not indeed mean that experimentation and observation should not be part of a good elementary teaching of mathematics.

[27] The Site is at www.inrp.fr/lamap or at www.lamap.fr

[28] The project « Eratosthenes » is described in *Mesurer la Terre est un jeu d'enfant* (2003) H. Farges, E. Di Folco, M. Hartman, D. Jasmin, Le Pommier, Paris.

[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 : *La science institutrice*, Odile Jacob, Paris, 2002 ; *La sagesse du physicien*, L'œil neuf, Paris, 2005 ; *Qu'est-ce que la culture ?* (collective), Odile Jacob, Paris, to be published, 2006.