COLLOQUIUM: **The cultures of Science**

Lecture given on October 20, 1992, at McConnell auditorium, Smith College by Louis MICHEL, Five College Distinguished Professor Mathematical Sciences.

SCIENTIFIC CULTURE

It might be easier to write a whole book on scientific culture than to explain it in one hour. Tonight I will try to show the most important characteristics of this culture. But I will mainly develop only one aspect of the scientific culture: it gives a common history of mankind; it is a universal culture.

Explaining the nature of scientific culture can be done sometimes by opposition. For instance, we must distinguish science and technology. The latter is much older in the history of man: the making of fire half a million years ago, the development of language, of hunting tools .... We do not really know this history. Were there different species of men? We do know, from scientific studies: paleontology. archaeology, that the Neanderthal men and our ancestors lived in the same period, sometimes in the same region. They even occupied some very same caves, but surely not at the same time! For the last thirty thousand years our ancestors have left us some very moving traces of their lives. They made drawings, related mainly to hunting, of real artistic value. They buried their dead. At least ten thousand years ago came the discovery of agriculture, the taming of some animals, the production of pottery mainly to make containers, navigation on water which allows to carry much heavier bundles than on land (note that the wheel is not so useful when there are no roads!). It is remarkable that each of these seminal inventions was made in several occurrences, *independently*, in places far apart. This is also the case for the invention of writing: at least five thousand years ago, writing was started and developed both by the Chinese and, in the middle East, by the Sumerian, and somewhat later by inhabitants of the Indus valley, and finally by the Mayas in Central America. Only in the case of Chinese has there been no break in a continuous evolution up to the present. Chinese ideograms are also used in part to write unrelated languages (Japanese, Korean). Sumerian and many Sumerian ideograms were used a long time after Sumerian became a dead language (with no known related ones); but the semitic people who adopted their cuneiform writing transformed it into a syllabic writing, which was adopted by many other nations, for instant the Indo-European Hitties and Persians. Finally it was transformed into several alphabetical writings. Nearly all presently used alphabets (with the exception of the Korean one) seem to be related to a semitic alphabet used three thousand years ago by the Phœnicians. I had the occasion to see in some detail how, in the XVIII$^{\text{th}}$ century B.C., the Assyrian merchants invented the fractions they badly needed: those of denominators 2,3,4,6; how cleverly they were doing in their computations the necessary rounding off; that was made by highly trained specialists (this was still true in our Middle Age).

Although it requires a lot of intuition, patient observation and allows some so-called primitive ethnic groups to live in an environment in which the great majority of us would not survive, the trial and error method is not yet Science. *It lacks the reflection which will establish from these facts a new kind of abstract fact corresponding to logical truths.* In antiquity, there was a unique mature development of science: it was made by the Greeks during the last five centuries B.C. For instance, about fractions, they first naturally believed that every number [1] could be written as a fraction of integers; but rightly some doubts occurred, a sane scientific controversy arose, and it was finally proven that $\sqrt{2}$ is not such a fraction (and this is the case of "most" numbers). To our knowledge this proof was not established independently in any other culture. I am sad to see that, more than two thousand years later, this beautiful and finally very simple result is not yet taught in any elementary school[2].

Science could not have been created before some technical development was attained (although the Greeks at that time had a poorer notation for numbers than the Chinese, the Hindus and, nearer to them, some semitic countries). For the first sixteen centuries A.D. the development of science was slower than that of technology. Mainly in Asia, in Europe and in the northern part of Africa, many technical inventions were introduced, often in different places: metallurgy, an already two thousand year old technique in many places was tremendously developed (over a thousand years ago, giant bronze statues were made in eastern Asia); men harnessed new sources of energy such as water mills and, more in the West, wind mills. New methods of communication were introduced; printing with mobile type was spread in China (probably from Korea) six or seven centuries before Gutenberg. The Chinese invented paper and used it not only for writing but also for money! That is what Marco Polo found the most astonishing of all extraordinary things he reported about life in China. Before the Christian era, there was already a tenuous, but continuous chain of trade from the West of Europe to the East of Asia. The Phœnicians and the Greeks were very audacious and able navigators; the same is true later of the Vikings, the Arabs, the Chinese, not to speak of the Polynesians who settled in islands everywhere in the Pacific! They all used stars; but the invention of the compass by the Chinese spread to the West and helped tremendously the possibility of intercontinental navigation. We all know what happened five hundred years ago this month.

What happened to Science during the same period? It flourished in the Greek culture for several centuries A.D., remarkably well in mathematics and also in astronomy and geography. Not only did the Greeks know that the Earth is a large spherical ball, they measured its size with an accuracy better than ten per cent. With the Ptolemaic system, astronomy had become an "exact science" which reached so great a precision that the 26000 year period for the precession of equinoxes was discovered and computed. This scientific knowledge diffused slowly, mainly among the Islamic cultures, from South West Europe, through North Africa up to Central Asia. Astronomers began to perceive the size of the solar system. Scientific method was slowly applied to many fields; in the West, mainly by monks. One of these fields, very important

[1] Those we now call the "real numbers".

[2] Here is the proof; assume that $\sqrt{2}$ is a fraction p/q written in simplified form, i.e. p and q are integers with no common divisors. Taking the square: $p^2 = 2q^2$ shows that p is even and we can write $p = 2r$; the relation becomes $2r^2 = q^2$; this implies that q is also even in contradiction with the assumption of the simplified form of p/q. The numbers which can be written as fractions are called rational; most real numbers are not rational. The proof of a precise technical meaning of this statement was made by Cantor last century. The proof does not require much technical background and could be written in one page. It raised deep questions on the structure of mathematics. The first answers came in a surprising way from Gôdel in the nineteen thirties; they were completed by P. Cohen in the beginning of the sixties.

for the rich and the powerful, was medicine; the Jews excelled in it, probably due to their situation at the interface of several cultures.

Even for scientists, it is often difficult to decide what is a scientific problem and what is not. We are often confronted with that difficult question in our work; the answer depends on the state of development of science. A thousand years ago, and much before, it was a natural question to wonder if the positions of the celestial bodies (sun, moon, planets) moving on the background of starts, had an influence on our personal lives. Often, before making important decisions, rulers had their horoscope made. If they were well made, I mean with precise information on the planet positions, and if they have been preserved, they are now very useful to historians for chronology! Thanks to this interest in astrology, the motions of heavenly bodies were studied with precision and astronomy was developed in the far East, in the Islamic world and in central America. Although it developed later in Europe, there, in the XVI$^{\text{th}}$ century the quality and the precision of astronomical observations tremendously increased and made obsolete the Ptolemaic model in which the sun and all planets were revolving around our Earth. The Tycho Brahe model introduced minimal change: Mercury and Venus rotate around the Sun, all the other bodies rotate around the Earth. The Copernican model was more revolutionary: in it, all planets except the Moon revolve around the Sun and *our Earth is simply one of them*. For forty years not one astronomical observation could decide between these two models. But the Copernican system had a remarkable and very esthetical structure which was emphasized by the empirical and very precise laws found by Kepler at the beginning of the XVII$^{\text{th}}$ century[3].

These laws led to Newton's theory of "universal gravitation", the comprehensive theory which applied equally well to celestial and earthly bodies. It marks the beginning of the modern era for science. It explained immediately the influence of the moon on the tides and predicted the flattening of the earth at the poles. It is only in this century that we have understood the large climatic effects due to tiny variations in the relative motion of the earth around the sun that can be computed with Newton's theory.

Here is another example: in the XVI$^{\text{th}}$ century, Francis Bacon noticed the likeness of the shape between the West coastline of Africa and the Eastern one of South America. This was a natural question but not a scientific problem. It became so only when similarities between these two parts of continents were found by geologists and when the theory of evolution lead to the study of common ancestors in part of their flora and fauna. At the beginning of this century Wegener proposed the hypothesis that, maybe two hundred millions years ago, most present-day continents parted from a single one. From the beginning of the sixties scientists have made a global and thorough study of the continental plates, their drift, the effects of their collisions or their breaking.

[3]The distance of each planet to the sun is not a constant: its orbit is an ellipse with one of the foci S occupied by the sun; the speed of the planet P is not a constant but the variable radius SP sweeps a constant area in a constant unit of time. Finally there is a simple relation between the size of the orbit and the period of revolution. Kepler added even too much in his "Harmonice Mundi" by finding a geometric relation between the six known planet orbits and the five regular polyhedra.

One could give so many other examples of the genesis and development of scientific knowledge! And do not forget that there are also many stillborn scientific hypotheses. That does not mean that scientific progress is the replacement of obsolete theories by new ones; this is no longer the case in the modern era of science. A scientific theory is based on hypotheses verified on a given domain of validity; strikingly, the domain of validity of the theory is generally much larger; but we expect that it has some limits that can be reached one day. It is hard but fascinating to work on this frontier of validity of the established scientific knowledge, in a incomprehensible world of facts. New concepts have to be conceived, often in conflict with those we were using. Someone, often one of the few existing geniuses, formulates the needed concept(s) in an illuminating way for those who are working in the full darkness. Then comes the euphoria of finding verifications and applications of the new theory, mainly done by a new generation of scientists. Indeed a new intuition is necessary and evolution of science thrieves on the successive replacement of generations. Our understanding of old theory is deepened, as a very useful approximation of the new theory. But the old one is still the most commonly used in its validity domain.

I hope it is clear to you that if a vast and well organized collection of facts (either due to observation or to experimentation, depending on the field of science) is a necessary foundation of science, laws and concepts are its essential constituents. Indeed the aim of science is not only the understanding of data, but manly the prediction of new phenomena, Then some scientists, often by techniques at the limit of present possibilities, verify their existence; the most interesting discoveries occur when the new facts are in contradiction with the prediction; this uncommon events always leads to important scientific progress. More and more often now these "revolutionary new facts" are simply artifacts which may make scoops for a new media; soon a more strenuous or clever experimentation finally supports the present theory, but that does not make news.

Sometimes, unethical behavior of a scientist makes the news; indeed this is rather exceptional. To participate to the progress of science, many qualities are absolutely necessary:

honesty; the results obtained without it have practically no scientific value and some colleagues will need our results for their own work;

a critical mind; exceptions to scientific laws or contradiction to well known facts may always appear; indeed scientific laws and results depend of the neglect of influences and effects which might be no longer justified in the new situation. For example, the results of Barbara McClintock on the wandering parts of DNA contradicted our ideas on heredity and DNA; it took a long time to recognize their great importance. In 1984, aperiodic crystals with icosahedral symmetry were found although it was proven in all crystallography books that that was impossible;

a *great curiosity*; not only for studying new scientific problems, but also to recognize the value of unexpected or unwanted results. Fleming was annoyed by his failure to obtain a normal growth for a culture of bacteria he was working with, but he discovered the cause: penicillin. When in 1934 Lawrence and Livingston were running their first cyclotron, they had to stop regularly for a fraction of an hour because of the radioactive background. they failed to recognize that this nuisance was due to

the creation of new radioactive elements, while the Joliot-Curies who were expecting artificial radioactivity, proved experimentally its existence in one week end! But two years before, they had not understood the nature of phenomena they had been first to observe: the production of neutrons and the production of positrons (the particle of antimatter). Penzias and Wilson fought for months to eliminate the noise of their ultra sensitive receptor before they realized that it was a real effect due to the 3^{o} K cosmic photon background; they did not know that it had been predicted twenty years before by Gamow. Making science is not as straightforward as in fairy tales.
humility; we must be ready at any moment to see our results superseded; and we are confronted with so many facts that we do not understand completely or not at all. And
perseverance; a lot of it!

That science is never completed, never finished, but always in evolution makes us very optimistic. Moreover, the application domain of the scientific method is being continuously enlarged and it would be foolish to try to predict its limit. This does not mean that all human activities can be guided by science as some philosophers (and few scientists) have proclaimed during the last or the present centuries. But I *must emphasize a very specific aspect of scientific culture; it is independent from national cultures, the metaphysical views, the race or the sex of the scientists who enrich it or of those who appreciate it and teach it.* This universality is absolutely unique among the different cultures. The scientific method, a precious inheritance from two thousand years of dedicated lives, guided a deeply ingrained human activity which gives to mankind its own history. More than ten billion years ago the big bang occurred; the Earth is only 4.6 billion years old. Its rich variety of chemical elements (including the constituents of our bodies) were made in stars which exploded and collapsed. Since the appearance of life, probably 3 billion years ago, a very long evolution of the species has occurred, depending sometimes on global catastrophe as was the case 63 million years ago with the impact of an asteroïd which produced a 180 kilometer crater in the ocean, east of Central America; it was found this year by scientists in the region that their theory had predicted. The dust produced provoked an ecological catastrophe by occulting sunlight; it eliminated all large terrestrial animals. Finally, the first human being appeared two millions years ago. Presently the study of our mitochondria seems to suggest that all living men and women may have a common ancestor: a women who lived less than 150 thousand years ago. Very recently scientists have been able to cultivate and analyze some DNA of fossils. When this new research tool is more developed[4] it will tremendously help paleontologists and archaeologists to recover the history of prehistorical periods. And it is by applying the scientific method that we can understand again most of the writings whose meaning were lost.

Not only does science gives to mankind its history, our common past, it has already definitely changed our future. The most important factor of this change over the past hundred years is the spread of the scientific method for health that we call hygiene. I cannot refrain from noting that Louis Pasteur, who established its scientific basis, had no training as physician. His use of the anti-rabies serum that he prepared,

[4]And many other such scientific tools have to be invented!

and many other of his famous deeds, would nowadays be considered as illegal in his own country and several other ones. Yet, the introduction of hygiene has destroyed an equilibrium of population by increasing enormously the average life expectancy. This phenomenon has been amplified by the spectacular progress of medicine and surgery. Each nation, each type of culture may like it or not. Indeed average life expectancy is increasing in some countries and decreasing in others, as presently in USA and in former USSR. The value to be given to each human life is a question which transcends present scientific culture. Such a fundamental question has to be answered by political and moral authorities, and ... by each of us.

This does not mean that science has no philosophical or ethical impact. For instance, the concept of evolution and progress, which were foreign to most classical cultures, were introduced in science in the XVIIIth century.

Nowadays Science and Technology live in complete symbiosis. One cannot be developed without the other and there is a full gradation from applied science to technology. When I speak of Science, I mean *this urge of curiosity, this need to understand, this hunger of knowledge, this contemplation of Nature, this fascination that makes us work so hard, because we feel it necessary* and it can bring also deep pleasure: not only the pleasure of discovery and knowledge, but that of a strong esthetical emotion given by the beauty of scientific theories and the harmony of Nature. When Jacobi was asked why he was doing mathematics, he simply answered[5] “Pour l’honneur de l’esprit humain”.

We, the scientists, must be aware of the possible technical applications of Science, and I profoundly respect those who use their scientific talent for practical applications. But the responsibility for the consequences of these applications is in the hands of those who make and use them. However, if among the population there were no longer a sufficient number of persons interested in cultivating Science and making it progress, our technical civilization would collapse rather rapidly ....

So, for those who are able to do it, we feel it a duty to communicate our scientific culture to the next generations and to all those interested to know it. What worries us is that the huge majority of living human have no desire to understand what science is and what they can expect from it. This is obvious for those few who are proud of their complete ignorance of scientific culture. But it is tragically true of the many who believe they know what science is, but are in complete error. How to explain science to people who have no idea of what it is? It is as difficult as to trying to explain to a person blind by birth what is light. From everyday experience we know that for persons never exposed to scientific culture, it is impossible to recognize science from fake science; to distinguish phony claims from a genuine scientific controversy. Such a confusion on the heads of those who have to make decisions might lead to disastrous consequences, as was the case, in the fifties, of genetics in Soviet Union when Lysenko’s “theory” was supported by those in power. But the same confusion in the majority of the citizens of a democracy is as dangerous. It is rather depressing to see so many citizens of our so called “advanced societies” to be backward by many centuries, for instance when they still believe in astrology.

[5] For the honor of mankind.

Of course rational decisions can be based on second hand knowledge, through experts, specialized institutions, ... Is this satisfactory? On many problems genuine experts may disagree, because they might even be in a preliminary stage where the formulation of the problem is not even clear! If this problem has important implications for the future (a striking example of such a problem is the effect of our industrial technology on the future climate) the best advice that experts can give is the urgent necessity of a scientific study of the problem and a great caution in our policy of action since we do not know all its consequences.

The solution of most of the existing problems confronting humanity need a rational approach and the help of the scientific method. This requires that scientific culture should not be confined to a small minority. In the present world, I think there should be no education without a minimal requirement of scientific culture. This applies a fortiori for "higher education". Do not see that as a kind of hegemonic ambition of a scientists! Indeed I believe also that there should be no higher education without the study of a foreign language in order to reach a genuine knowledge of at least one foreign culture.

In preparation for this colloquium, like several other participants, I guess, I read again C.P.Snow: "The Two Cultures and a Second Look" a re-edition of the famous "The Two Cultures and the Scientific Revolution" which appeared in 1959, augmented by the author's reflections "in the light of various comments and the passage of four years". It is very interesting and pleasurable to read this great thin book. It is also a generous text (some might say utopian) that Snow first thought of calling "The rich and the poor" and he tells us "I rather wish that I had not changed my mind".

Many saw in this book only the harsh critic of the traditional culture and of its pretense to be the whole of culture. I think we all have to be more modest. First there are many traditional cultures, each one based on a language with a more or less great span on our planet, a more or less old history and rich literature; the most widely spoken language is Chinese and it has the longest continuous record of writings. As a Frenchman I was amazed to see Snow taking all his examples from British and U.S. culture of history, as well as from German, Scandinavian and Russian ones, without ever mentioning the French ones. And I disagree with him when he writes "The Scandinavians .... are handicapped by their practical need to devote an inordinate amount of time to foreign languages". Finally, we scientists, know too well the difficulties we have in understanding each other: what C.P.Snow writes about the discovery of parity violation in 1956 is inaccurate. I can also understand the frustration of some readers, because the scientific culture is much spoken about in this book, but not really described. I felt that was my duty to do it here.

I would like to end this talk by giving you a few glimpses of the cultural life of many scientists I have known. I began to do research forty seven years ago in a French laboratory. I had the possibility in 1947 to work on cosmic rays in Patrick Blackett's laboratory in Manchester, England. Léon Rosenfeld came, in 1948, as professor of theoretical physics and I asked to work in his group: we were eight to ten young physicists from at least six countries on three continents. When I asked Rosenfeld questions about my work, I always received a good general answer and the references of half a dozen papers to study. These papers were in German (the most widely used language for theoretical quantum physics before the war), in English, in French, in Italian (among them, those of E.Fermi and E.Majorana) in Russian (Rosenfeld had to help me at the beginning for reading some of Landau's papers). Do not forget that reading technical papers is easier than reading the classic literature (of course, I mean from the linguistic point of view!) There was an agreable and culturally rich social life; the Blacketts and the Rosenfelds were so cultivated! We knew also the families of colleagues from other departments and some families outside academia. Our first son was born there. We moved to Copenhagen in 1950 at the Universitetets Institut for teoretisk Fysik, which is now the Niels Bohr Institut.

In the twenties and the thirties, this was the main center for theoretical physics. So many of the great physicists had come there in their youth and were coming regularly: Bohr's influence had been tremendous. The senior physicists were well known and we were at any time between fifteen to twenty young ones; our origins were more varied than in Manchester and our professional and family relations were much more intense[6]. Bohr was housed in a huge mansion built by the founder of the Carlsberg brewery who requested it to the Danish kingdom to be used by the most famous Dane. The families of young physicists were receiving by the Bohrs and we knew his sons' families. For Christmas we were all in Bohr's house, singing around the Christmas tree; Bohr had a huge and very exotic collection of toys (a toy was a usual gift to bring him) and he helped each of the many children to play with them. Margarethe Bohr was a exceptionally kind and thoughtful hostess. She came to see Thérèse at the hospital at the birth of our second son; and later we received the Bohrs with some Danish friends. You can easily guess that this pattern of life influenced us profoundly. We always tried to follow on our scale this example, in our relations with my students and colleagues.

In 1950, when we arrived in Copenhagen, Bohr had just published his open letter to the United Nations; we were all discussing the expected effects of his message and the problem of international nuclear control. Then came the making of CERN, the first European laboratory. About ten nations were involved. The British were against it, but they joined six months after the international treaty was signed. As you may know, this forty year old laboratory near Geneva, which has progressively extended right on the border between Switzerland and France, has been quite successful in bringing back to the international level research on particle physics in Europe. It has also been a model of international collaboration which has deeply influenced the organization of all new laboratories with particle accelerators everywhere in the world; it has given an impetus and helped the creation of similar European laboratories in other fields of physics and other domains of science (astronomy, molecular biology, ...). Collaboration on a world scale is now the normal state in several domains of science, especially for those requiring coordination of observations and measurements all over the planet or by satellites. So many scientists have to live sometimes from several months to several years in a different country, collaborating daily with colleagues of different cultural backgrounds. Theoreticians and mathematicians move very easily[7];

[6]Among them was a young American couple on his first trip abroad. They stayed in Copenhagen and he became one of the Danish Nobel prize winners.

[7]From Copenhagen. we moved in 1953 to Princeton. So many great physicists and mathemati-

indeed their activity does not depend on high quality or heavy equipment (but they need good libraries). The professional curiosity of scientists comes generally from their natural curiosity and they are normally inclined to become multicultural. The deep concentration and hard effects required by scientific research make relaxation necessary; it can be through sports or any hobby; often it is music. In general scientific meetings or summer schools I attended, a concert was given by some of the participants.

It is true that scientific research may lead to fierce competition with dirty tricks, that scientific collaboration can end in ferocious hatred and sometimes in law suits; there are many famous examples, mainly in this country. But you can choose your style of life. Most of my scientific collaborations made me understand better the cultural background and the character of those with whom I was risking my professional reputation. These collaborations have usually been transformed into lifelong friendships. To-night I thank all these friends, not forgetting those no longer living; together we shared our different cultures and enriched our common scientific culture.

cians at the University and at the Institute for Advanced study! Its director, Robert Oppenheimer, was so kind to us. The two years we lived there were so rich. Our first daughter was five months old when we returned to France to settle there.