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Scientific Knowledge and the Citizen

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Abstract

How can citizens become more aware of science and how it proceeds in order to be able to form their own opinion on science based problems concerning our environment and thus participate in taking decisions relating to technical matters? Scientific knowledge is also part of human culture and contributes to the evolution of human values like faith. What role can scientific academies play in improving the trust between the public and science?

It is generally recognised that science as the basis of modern technology has immensely contributed to the evolution of society during the last 200 years. By 'science' I mean in this article 'natural sciences' (physics, chemistry, biology, etc. but not humanities or economics). Science and technology are attacked as being at the origin of many of the problems we are facing today. Sometimes it is claimed that we are entering the era of post-enlightenment and that the advantages hoped for like freedom and wellbeing for everybody have not been attained and that instead of providing high standards of living, technology leads to crisis in many areas of human existence. In order to find ways to improve the situation and to exploit fully the social power of scientific knowledge it seems necessary to discuss the relationship between science and technology and their impact on society and to clarify some misunderstandings and some wrong concepts. These misapprehensions are partly due to erroneous presentations in the media but also because of premature public announcements of scientists driven by too much ambition.

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1. Does the normal citizen understand how science works?

To the general public, the image of science lies between the two extremes—on the one hand science represents the absolute truth and on the other hand, science is a social activity and hence depends on historical conditions, contingencies and is therefore untrustworthy. Both images are, of course, wrong.

In the progress of science one should distinguish between two phases: the first phase in which the personality of the researcher is essential for choosing his method of work when he explores new domains, following in some cases more systematic paths or in other circumstances trying to proceed by trial and error. During this phase, contact with other scientists is essential. The image of the lonely genius as presented in many works of literature is completely wrong.* Even Einstein, perhaps the most outstanding example of the solitary mastermind, depended on interactions with other colleagues. Usually only after many wrong trials and many useless detours do final results emerge. Even those may be questioned by the results of other scientists and more work may be necessary to come to a definite solution. Also what is called the intuitive process can be essential in this phase, but intuition alone, as important as it may be for the progress of science, is not sufficient. Intuition alone may be crucial in other domains of human activities like in arts, but in science another phase has to follow.

It is the second phase, the phase of consolidation and verification, which provides the content for textbooks and handbooks used by students. There everything looks logical and straightforward and all the detours are suppressed (which sometimes gives the wrong impression that science is boring since it is not about surprises and intuition). In this phase interpretation, theory must be compared with facts which in natural sciences are measurements, i.e. numbers. Sciences are based on quantification and the empirical results are represented in mathematical form. This whole process requires a close collaboration between theory and experiment and implies a lot of hard and tedious perspiring work. It can be achieved in most cases only by cooperation of several or even many scientists and refutes the pictures of the lonely genius solving all the riddles in his study by thinking deeply. The media and also the public, of course, prefer human heroes which does not do justice to the fact that modern science is mainly based on cooperation. And progress is made mainly in small steps and not in a few breakthrough discoveries. James Clerk Maxwell, who is mainly praised for unifying electric and magnetic phenomena in the 19th century, added a final element to this unification by extending in his famous equations the theory from static to varying electromagnetic fields—after Michael Faraday, Hans Christian Ørsted and others found in experiments the relationship between electric currents and magnetic fields. Even Einstein knew already the Lorentz transformation which is a key element of the theory of special relativity and he learned a lot from Riemann's geometry of curved space for his theory of general relativity.

In natural Science facts are based on measurements which can be put in numbers, in formulae and finally in mathematically formulated theories which not only reproduce all measurements but also allow predictions. This is one of the mysteries: nature prefers mathematics as a language! Considering the history of science we state that a first step was the penetration of physics by mathematics. Combined with quantum mechanics this helped us understand the structure of the atom, then the atomic nucleus and most recently, the structure of elementary particles and the forces acting between them. Of course always being guided and confirmed by experiments! Chemistry was in the beginning like all sciences, a purely empirical activity, (starting with the alchemists) and later became a real science only around 1920 when, thanks mainly to Linus Pauling, physics helped us understand the

* See for example 'The Physicists', a play by Friedrich Dürrenmatt

chemical bonding and reactions on the basis of the atomic structure. Molecular Biology is presently in a transition from empiricism to theoretical understanding, whereas genetics and neuroscience are still restricted to certainly remarkable but still empirical successes.

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2. Truths in the natural sciences and other human domains

The main difference between the natural sciences and other human actions is the difference between what is considered true: in science a result is recognised as 'true' only if it can be reproduced anywhere at any time. The ultimate authority is nature and not human power. If a young student produces a result which obeys this condition of reproducibility he would be right even if all great authorities are initially against him. This reproducibility provides great confidence in the applied results of science in technology. When social scientists occasionally claimed during discussions that all results of science are uncertain since they are dominated by social conditions, I asked them whether they trust a bridge which they cross or an airplane which they board.* Because of quantum mechanics airplanes have not become more dangerous!

This reproducibility is sometimes interpreted in the way that scientific results are considered to be eternally valid. Is this true? Yes and No! Media sometimes report about a revolution in science, what does this mean? Scientific revolutions do not imply that all existing knowledge is wrong but rather they restrict the validity of a special theory to a certain domain of parameters. For example relativistic dynamics does not imply the Newtonian mechanics is wrong but it means that the latter is valid only for velocities much smaller than the velocity of light. Quantum mechanics has not proven the invalidity of classical mechanics but has shown that it has to be modified when dealing with dimensions of the size of atoms. In these and many other cases the new theories include the old ones as asymptotic special cases.

Another problem which arises when scientific problems are discussed in public concerns the influence of errors. Results of measurements are expressed as numbers. No measuring equipment is free of imperfections and hence the results are affected by systematic errors. It is part of the experimental art to keep the systematic errors as small as possible or to estimate at least their size. The other kind of error is the statistical error. If we flip a coin the probability that one side will be up is 50%. However, if the coin is thrown 10 times we will find that one side is not up exactly 5 times, maybe 4 or 7 times. The simplest laws of statistics tell us that the deviation from the ideal expectation is proportional to the square

* Here, all the interesting philosophical discussions about reality and objectivity are neglected. They are very interesting from a philosophical point of view but as a practising physicist I ignore them as long as I am in the laboratory.

root of the number of trials. Therefore with 10 trials (square root of 10 is about 3) one has to expect a large error of about 30% which is reduced to 10% with 100 trials.* Therefore in certain experiments the statistical error can be reduced by repeating the measurement. The scientific result expressed by a number has practically no meaning without quoting at the same time the error, both systematic and/or statistical. In physics and chemistry this is a strictly followed rule and to a certain extent, errors are discussed also in medical research and some other fields. However, in public surveys this is mostly but regrettably neglected. Normally in a survey, about 1000 persons are interviewed which gives a statistical error of about 3%. Various results differ often by not more than this and hence have no relevance which is usually not mentioned and completely neglected.†

The importance of errors becomes even more crucial when scientific models are used to make predictions. Every model is based on certain assumptions depending on the present state of knowledge. The lack of knowledge can be taken into account by considering several models based on different assumptions and leading to diverse results. This ambiguity results, of course, in a different kind of systematic error. Unfortunately also in such cases the error is often not mentioned in public presentations of the predictions. The most drastic actual case is the prediction of climate warming. An enormous amount of interdisciplinary work has gone into achieving the best possible predictions. However, some parts of the complicated climate system are not yet sufficiently understood, for example the influence of clouds or the interaction between oceans and atmosphere. Therefore different models have been developed starting from different assumptions. The average of all these models gives the famous 2 ^{o}C which is used in all political discussions concerning the reduction of climate warming. In all the public discussions I have heard, the errors attached to this value have not been mentioned although they are at least of the same magnitude as the value of 2 ^{o}C itself. For political reasons this might be justified but certainly it is not a rational use of scientific knowledge.

Of course, science is studied by people who have favourite ideas and prejudices. They make errors and follow wrong paths. To study the history of science is therefore very important, in particular in order to demonstrate to young people its human side and how fascinating it can be. However, after the fog has disappeared only the verified results will survive as explained above and only these should be used in any application.

In summary the following remarks are pertinent: scientific knowledge changes in history, but not by invalidating old theories but rather by restricting their domains of application. In addition because of unavoidable systematic and statistical errors all scientific results are not absolutely true to any degree of precision and their uncertainties have to be taken into account for decision making. The lack of this understanding among the public and politicians leads to many misinterpretations and sometimes to wrong decisions. It will also have the consequence that a large part of the population might lose the confidence in science since they might get the perception that science is not reliable. How can one achieve a state where difficult political decisions on energy production and use, climate change, nuclear energy,

* The general role of probability in quantum mechanics cannot be discussed here. As far as measurements are concerned involving quantum mechanical phenomena the estimation of the statistical error is very similar although much more sophisticated than when throwing a coin.

† This is also true of most election forecasts that compare results of different parties or persons.

water and food supply, etc., are based more on rational arguments instead of being strongly influenced by emotional disputes?

3. Education and Political Decisions

The importance of education for the citizen has many aspects which cannot be discussed in all its aspects in this article. Only the necessity of providing to every citizen a minimum understanding of scientific matters will be considered.

We are living in an environment which is determined to a large extent not only by technical man made conditions but also by unavoidable natural dangers. Both succumb to the laws of nature. Every citizen should have a minimum understanding of those conditions in order to deserve the connotation of being an educated member of human society. The obvious solution is education should include not only reading and writing but also a certain understanding of the fundamental laws of nature as discovered by science. This is the main task for primary and secondary schools. Primary education should be compulsory for all children and in developed countries secondary education should be made available to a large part of the population. This is certainly a difficult but important task since it would at least take away the fear of some natural phenomena (and has successfully done it already for thunder, lightning, earthquakes etc.) which are still dangers but are understood as natural phenomena and not as expressions of the anger of gods.

Things become more complicated when it comes to understanding some modern technological developments. The scientific and technical environment is extremely complex and it needs specialists to understand and evaluate it. However, decisions related to such problems are very often major elements of the strategies of political parties or governments. They are even directly raised in popular referenda (examples are climate change, air pollution, genetic technology, chemicals against weed, nuclear energy etc.). In an ideal world one would hope that all citizens can be sufficiently informed to be able to make their individual decisions based on rational arguments.

This is, of course, an illusion grounded on the erroneous assumption that all people are equal. Some people are stronger, more beautiful or more intelligent than others. The basic concept of democratic thinking should be that the *chances* are equal for all, but not necessarily the *final achievements*. Hence we should not expect that the critical power of judgement should be the same for all citizens. Maybe scientists and other trained experts should have a special function in political decisions, a very difficult problem. Certainly, an objective of public education should be that the citizens understand in principle how science progresses as described above and how its results should be interpreted and applied. But one has to accept that a certain specialisation is unavoidable and indeed is the practice in most state systems with primary, secondary and tertiary education institutions. However, it is an open question whether citizens with different degrees of (scientific) education should have different degrees of influence on social decisions. If the answer is yes, it remains a completely open question as to which way this could be established in. But it is certain that a popular vote does not guarantee the most reasonable technical decision.

4. Science and Human Values

For the general citizen it is relevant to have at least a basic scientific knowledge not only to better understand and evaluate our technological environment, it also has some influence on our acceptance and formation of values.

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Since the era of enlightenment, scientific development has infiltrated general education in many countries to a sufficient degree that the population has been liberated from superstition and the belief that supernatural powers take a direct influence on human destiny. Kings and emperors are not anymore believed to be installed by the grace of god,* a concept that played an important role in Europe over centuries.

Our modern understanding of the physical world has deeply changed the relationship between science and faith. We know now that the age of the earth is about 13 billion years and not about 4000 years as it has been deduced from the bible and we understand the evolution of species, including man, as a result of evolution.† As a result, it is sometimes claimed that modern science leads necessarily to atheism and even famous scientists and politicians express themselves in this way. This and other wrong concepts concerning the relationship between science and religion are based on a misunderstanding of the progress of science.

As has been explained above, the 'truth' in science is based on observations reproducible anytime and anywhere whereas in religion it depends on revelation which is normally not repeatable at will. Hence, because of this fundamental difference in perceiving the world, there cannot be a conflict between science and faith. When Pope Johannes Paulus II visited CERN in 1983, I had the occasion to present to him this concept and he fully agreed. Hence it did not come as a surprise to me when a few years later Galileo Galilei was vindicated by the Vatican. When some time later the Dalai Lama came to CERN we came to the same conclusion. When I expressed my surprise that he fully agreed with the Pope he answered that he had dinner regularly with the Pope where they discussed such issues.

Miracles are essential elements of all religions, but in principle not repeatable. It is simply not possible to prove or disprove by methods of natural sciences any religious dogma, including the essential question whether god exists or not. Science provides only one aspect of human reality. Several other aspects apart from faith are not accessible to science. Beauty is one of them and science will not be able to explain to me why I like the paintings of the

*Although in some parts of society financial success is still considered to be a divine reward and astrology is still a much appreciated topic in some journals.

† Some of the formulations in holy scripts should be interpreted symbolically in the view of modern science and not taken literally

French impressionists and not those of abstract modern art, why I like the music of Mozart and not that of Stockhausen. The mysteries of the various forms of human love will never be fully explicable to science and perhaps one day one might be able to understand better the mechanism of the human brain based on neurobiology, but consciousness, ethics and free will will remain outside the realm of natural sciences as defined in this article.

"The search for unification, for unity, is one of the fundamental aspirations of human existence."

As a physicist I can still be emotionally impressed by looking at the stars on a beautiful summer night even when I know how they produce their energy and that they will exist only for a certain numbers of years. And I still consider it as a great mystery how the world came into being in spite of knowing the modern cosmological model which explains the evolution of elementary particles, atoms, molecules, dust, stars and galaxies but starts time and space with a 'big bang' during which time and space were 'created'. What is the 'big bang'? I once read that to the question 'what existed before time?' Saint Augustin replied 'God has created the purgatory for people who ask such stupid questions'. When I explained to Pope Johannes Paul II during his visit to CERN that in our machines we create matter from pure energy he corrected me by saying thus: '*creation* is my business, you can only *produce* matter'.

According to the ways in which we explore or perceive the world we shall find different aspects which seem not to provide a coherent picture or even to contradict each other. It is like comparing the different projections of one object. The shadow of a dinner plate will be a circle in one direction but will be closer to a straight line in a different projection. Which one is true? They are both stemming from the same reality and only by combining all projections we shall get a better understanding of the reality behind.

It seems that human beings need in addition to rational thinking a metaphysical 'narrative'. Can sciences contribute at least indirectly to establish such a narrative and the ensuing human values? Maybe, maybe not! Some general principles accepted in sciences may provide some hints. As far as we know today the laws of nature are universally valid—everywhere on earth, in the whole observable universe and at all times. Should one endeavour to find similar general laws for human ethics? Are 'Human Rights' as defined by the United Nations at least an approximation of such general laws? At least in science we have learned that tolerance, non-discrimination of races, faith and mentalities and mutual respect are positive values for the development of society.

In sciences and particularly in physics we aspire to explain the enormous multitude of phenomena by a theory based on as few assumptions as possible—a 'theory of everything'. This search for unification, for unity, is one of the fundamental aspirations of human existence. It allows us to put the multitude of phenomena into a logical scheme and maybe it is the basis for logical thinking. However, in physics we have learned that there will never be a complete theory of everything. Exploring nature is sometimes compared to unveiling an existing unchangeable painting. This is a wrong comparison, since the natural sciences are not as automatic and uninspired. Indeed, in order to formulate the laws of nature the appropriate concepts have to be invented first. The conservation of energy, one of the most fundamental laws in physics, can be formulated only when, after many years of experimental and theoretical work, the differences between the concepts of energy, work and action are clarified. By developing new concepts based on empirical observations new realms of nature can be opened to research, e.g. the concept of electric charge was at the beginning of electricity. The understanding that there will never be a theory of everything in the natural sciences might perhaps be a lesson for other sciences and human actions.

"Could WAAS play a greater role as far as global issues are concerned?"

5. The Public and the Role of Academies

Exploring nature to understand from where we come and where we are going to is one of the noblest human activities, independent of the practical use of results. Therefore science as such because of its deep cultural value should be free to choose its targets for research and should not be limited by political or ideological ideas—a message that should be transferred to the citizens. Scientific academies should contribute to this task.

The results of science become the basis of technologies which can be used for the better or for worse of society. To decide which technologies should be developed and which suppressed is not the responsibility of the scientists alone, it is a decision to be taken by politicians based on the democratic will of the citizens. Which technologies to support and which to ban then becomes a question that has become extremely challenging because of the complexity of technical problems and the progressing specialisation. Democracy is partially based on the assumption that the 'politically educated citizen' ('der mündige Bürger' in German) would be able to form his own judgement. This is an illusion. Certainly the educational systems have made it possible for practically every citizen to understand better our environment and the public networks allow everyone to obtain immediate information on whatever topic is of interest. However, a few clicks on internet pages cannot replace many years of specialised studies. So how can citizens form their opinion, whom should they listen to? The media are often not neutral in their reports, they are influenced by economic or political pressures. Neither can individual scientists be considered as neutral and reliable sources of information. Scientists have their ambitions, they are proud of their own achievements and are after all human beings with their prejudices. For every dispute on a technical problem concerning society one will be able to find individual scientists who are in favour or against. In the past some outstanding scientists had managed to acquire sufficient confidence among politicians and in the media and thus their messages had a certain weight. Unfortunately this happens much rarer today—media prefer beauties or footballers who are much more attractive than scientists.

Could scientific academies or learned societies play a useful role in informing the public? I believe this is the case if certain conditions are met. The studies, analysis and recommendations must not be biased politically, ideologically or economics-wise. This is trivial but not easy to achieve. It implies that the organisation must be financially independent from economic firms and political parties or other pressure groups and it must gain the confidence of the public which takes a certain time. A few organisations come close to this ideal, like the National Academy in the USA, the Royal Society in the UK or the Leopoldina in Germany. However, their influence on governments and media and hence on the public is still rather limited and in most cases restricted to national problems. Could WAAS play a greater role as far as global issues are concerned?

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