The Problem of Scientific Uncertainty

Ragnar Fjelland

Centre for the Study of the Sciences and the Humanities

University of Bergen

Summary

In a certain sense uncertainty and ignorance have been recognized in science and philosophy from the time of the Greeks. However, the mathematical sciences have been dominated by the pursuit of certainty. Therefore, experiments under simplified and idealized conditions have been regarded as the most reliable source of knowledge. Normally, uncertainty could be ignored or controlled by applying probability theory and statistics. Today, however, the situation is different. Uncertainty and ignorance have moved into focus. In particular the global character of some environmental problems has shown that the problems cannot be disregarded. Therefore, scientists and technologists have in many ways come into a new situation. This situation encompasses totally different problems than scientists and technologists are traditionally trained to deal with. The new situation requires interdisciplinarity, and in general a "democratization" of science is required.

Introduction: The problem of uncertainty

One might argue that scientific uncertainty is no problem at all, because we decades ago learned from the philosopher of science Karl Popper that all knowledge – including scientific knowledge – is uncertain. The prevailing view in the 1930s was that scientific knowledge is acquired by inductive inferences. Against this view Popper argued that universal statements cannot be justified in this way at all. In the opening page of *The Logic of Scientific Discovery* (originally published in German in 1934) he says about inductive inferences:

> [...] any conclusion drawn in this way may always turn out to be false: no matter how many instances of white swans we may have observed, this does not justify the conclusion that all swans are white. (Popper 1972: 27)

According to Popper inductive inferences cannot even be "probable inferences". Not thousand white swans can verify the statement: "All swans are white", but just one not-white swan can falsify it. Therefore, there is an asymmetry between verification and falsification.

I will restrict myself to mentioning three problems with this view. First, Popper has a very simple view of scientific knowledge as consisting of universal statements of the type: "All swans are white". Second, according to this view, uncertainty does not come in degrees: All knowledge is equally uncertain. Third, contrary to Popper's view the pursuit of certainty is a chief characteristic of modern science.

However, there was one time in European history when the intellectual attitude was close to Popper's ideal. That was the time in the fifteenth century that/which we call Renaissance humanism, with philosophers like Erasmus and Montaigne. As the word "humanism" indicates, it was based on a human perspective, characterized by an awareness of the limits of one's own perspective, the acceptance of uncertainty, the imperfection of man, and, therefore, a tolerance towards other opinions.

Renaissance humanism is often regarded as a predecessor of the Renaissance of the seventeenth century, when the scientific revolution took place. However, I agree with the philosopher of science Stephen Toulmin who in his book *Cosmopolis: The Hidden Agenda of Modernity* (1990) argued that the Renaissance, including the scientific revolution, was rather a counter-Renaissance. The human perspective was replaced by the ideal of an absolute perspective, which defined objectivity in modern science. He agrees with the traditional view that the birth of modern science, and of modernity, can be dated to the first part of the seventeenth century. However, he argues that modernity has two different roots. One root is the scientific revolution of the seventeenth century, with people like Galileo, Descartes and Newton. The real revolution, though, was the Renaissance humanism that took place two hundred years before.

Toulmin sums up the transition that took place during the scientific revolution in the following points:

- From the oral to the written: formal logic was in, rhetoric was out.
- From the particular to the universal: general principles were in, particular cases were out.
- From the local to the general: abstract axioms were in, concrete diversity was out.
- From the timely to the timeless: the permanent was in, the transitory was out.

According to Toulmin modern science is characterized by being based on an abstract ideal, “logical systems à la Euclid”. Hence modern science has been mostly concerned with the simple, idealized, stable and uniform. One indication of this is the importance of laws of nature, being regarded as universally valid. (Toulmin 1990: 183)

Although modern science and technology has given us an increased control of nature, reducing uncertainty, it has also adverse effects. One typical example is the case of cow madness. BSE (bovine spongiform encephalopathy, “mad cow disease”) was first discovered in 1986 in Great Britain. It is a neurological disease in cattle that affects the central nervous system, mainly the brain, which gets a spongy consistency (hence the word “spongiform”). Animals who are affected by the disease get diminished muscle coordination and movement. The disease has an incubation period of between two to five years, there is no treatment, and the animals normally die within one year after the disease has broken out. The occurrences had an epidemic like increase in Great Britain. In the first ten years after the disease was discovered, there were 150,000 cases of BSE. With the help of large-scale measures the disease got under control.

It quickly became evident that BSE has some common traits with a disease that infects people, Creutzfeldt-Jacobs Disease (CJD). Both diseases affect the central nervous system, and the victim of the disease degenerates and dies quickly; a special protein, the prion, causes both diseases. The idea that there could be a causal connection between the two diseases, for example, that people could get CJD by eating meat from cattle infected with BSE, therefore quickly emerged.

Even though there are some indications that there is a causal connection between BSE and CJD, we are, even today, not certain. BSE is an example of a new type of risk we find in the industrial society: a risk that is caused by humans. Everything suggests namely that BSE is a product of modern agriculture. In all likelihood BSE was spread because meat residue from cattle was added to cattle feed. Use of such cattle feed is a part of industrialised agriculture. In this respect BSE is an example of the new type of risk that the sociologist Ulrich Beck addresses in his book *The Risk Society*, where in the introduction he says the following:

> The gain in power from techno-economic "progress" is being increasingly overshadowed by the production of risk [...]. In advanced modernity the social production of wealth is systematically accompanied by the social production of risks. (Beck 1992: 13)

In this article I will first give a brief outline of the ideal of modern science that emerges during the scientific revolution. Then I will examine a traditional treatment of uncertainty and risk. Afterwards I shall examine some of the problematic aspects of this approach, and finally I will give an outline of an approach that adopts a broader perspective.

The scientific revolution and the pursuit of certainty

The scientific revolution, and, therefore, the birth of modern science, took place during the first half of the seventeenth century, and Galileo is usually seen as a key figure. This revolution is characterized by the pursuit of certainty. This pursuit is motivated by a mathematical scientific ideal, and we can draw a line from Plato, via Galileo and Einstein, to Hawking and "theories of everything". The empirically minded reader may find it strange that I associate modern science with Plato's theory of ideas. Nevertheless, as the French historian of science Alexandre Koyré has pointed out, Platonism represents an essential aspect of Galileo's science and philosophy of science (Koyré [1943]/1968: 34). Furthermore, Galileo's importance to modern science is indisputable. I want to point out, though, that the historical account is not essential. For the reader not interested in the history of science it is sufficient to point to the importance of mathematics in modern science.

Plato's theory of knowledge was inspired by geometry as the paradigm of knowledge, and according to Galileo "the book of nature" is written in the language of mathematics. However, there is an important difference between Plato on the one hand and Galileo and modern science on the other. Whereas Plato's reality was immaterial, Galileo's reality was material. Galileo called objective reality "primary sense qualities". Today we would rather use the term "matter". The essential property of matter is that it can be described mathematically.

Galileo recognized that a mathematical description requires measurements, and that measurements require controlled laboratory experiments. For example, he studied motion by rolling bronze balls down an inclined plane. The aim of the controlled laboratory experiment is to keep all or most factors constant. Only one or a few factors are varied at a time. These ideal conditions increase certainty. According to the traditional view, controlled experiments are merely simplification and purification of natural situations. We have to leave out some factors to make the problems manageable. Afterwards we "add back" the factors that were left out, and in this way we come closer to natural situations.

However, we do not only remove complicating factors. We impose artificial conditions on the object as well, because the ideal conditions are normally not realized in everyday life. Therefore, "adding back" may not be an easy task. There is an alternative, though. We may realize the ideal conditions through technology. From this point of view technology is a way of reducing uncertainty. It is interesting to note that Galileo was aware of the intimate relationship between the ideal conditions required to carry out experiments, and technology. In *Dialogue Concerning Two New Sciences* he pointed out that his own results had been proved in the abstract, and when applied to concrete cases they would yield false results. The horizontal motion would not be uniform, a freely falling body would not move according to the law, and the path of a projectile would not be a parabola. However, speaking of the difficulties arising by these limitations, he immediately adds:

> [...] in order to handle this matter in a scientific way, it is necessary to cut loose from these difficulties; and having discovered and demonstrated the theorems, in the case of no resistance, to use them and apply them with such limitations as experience will teach. And the advantage of this method will not be small; for the material and shape of the projectile may be chosen, as dense and round as possible, so that it will encounter the least resistance in the medium. (Galileo [1638]/1954: 251)

This does not only apply to technology, but to science as well. In their book *The Golem* Collins and Pinch (1993) give an illustrating example of this aspect of scientific practice. The example is an exercise to teach elementary school pupils to measure the boiling point of water. The pupils are told to put their thermometer into a beaker of water and read the temperature when the water boils. Hardly any of the pupils obtain the result 100 ^{0}C if they did not already know the answer. In the example of the book the results are like this: Skip gets 102 ^{0}C, Tania gets 105 ^{0}C, Johnny gets 99.5 ^{0}C, Mary gets 100.2 ^{0}C, Zonker gets 54 ^{0}C, whereas Brian does not obtain any result. Smudger boils his beaker dry, and bursts his thermometer. Ten minutes before the end of the lesson the teacher gathers all the pupils and starts the "social engineering" process: Skip held his thermometer in a bubble of superheated steam when he made his reading, Tania had impurities in her water, Johnny did not wait until the water boiled, Mary's result demonstrates the effect of slightly higher air pressure, and Zonker, Brian and Smudger have not yet acquired the required competence. After this lesson all the pupils are convinced that they have demonstrated that the boiling point of water is 100 ^{0}C, or they would have demonstrated it if there had not been a few local problems. According to Collins and Pinch this simple exercise demonstrate the essence of science:

> In the end, however, it is the scientific community (the head teacher?) who brings order to this chaos, transmuting the clumsy antics of the collective Golem Science into a neat and tidy scientific myth. There is nothing wrong with this; the only sin is not knowing that it is always thus. (Collins and Pinch 1993: 151)

Collins and Pinch have their own agenda (basically to show that science is a social construction) that I do not share, but I think this is a good illustration of the importance of idealization in science.

Traditional ways of handling uncertainty

After the scientific revolution it was gradually recognized that not all sciences can satisfy the requirements of the "exact sciences". One made a distinction between the sciences that satisfy the requirements (for example geometry, astronomy and mechanics: the "higher sciences") and the sciences that do not satisfy them (for example geology and medicine: the "lower sciences"). Probability theory and statistics were developed to make the "lower sciences" more exact. The basic idea was that if we cannot give an exact prediction of each single event, we can use "the law of large numbers" to predict some overall patterns. The philosopher of science Ian Hacking described this process in a book with a title that indicates the basic goal: *The Taming of Chance* (Hacking 1990).

In connection with risk one often distinguishes between subjective (perceivable) risk and objective risk. When we speak of subjective (or perceivable) risk, we focus on people's perception of risk, that is, how dangerous they believe something is. When we speak about objective risk, we focus however on the objective, often measurable, aspects of risk. There can often be a substantial difference between subjective and objective risk. Many people are more afraid of flying than of driving a car. Yet the objective risk of being involved in an accident is greater for driving than with travelling by plane. Experts on risk analysis therefore often see it is an important task to correct what they regard as people's biased perception of risk. For example, some experts consider people's fear of atomic energy plants and genetically modified food as irrational, and think that this fear can be reduced by increased information.

It follows more or less automatically that when the distinction between subjective and objective risk has been introduced, only objective risk can be studied scientifically. For example, it is said in an authoritative report compiled by the Royal Society of England about risk:

> The Study Group views “risk” as the probability that a particular adverse event occurs during a stated period of time, or results from a particular challenge. As a probability in the sense of statistical theory, risk obeys all the formal laws of combining probabilities. (Quote from Adams 1995: 8)

On the basis of such a definition one can develop mathematical techniques to discuss risk, and the calculation of risk has therefore developed into a technical discipline. Primarily the structure of risk analyses is the same as the structure of cost-benefit analyses. I shall therefore in the following paragraph give a short description of the structure of cost-benefit analysis.

A cost-benefit analysis has the following structure: At the beginning one has a problem that needs solving, meaning a decision must be made on which alternative to choose in a given situation. It can be quite a specific question, like for example what can be done to detect breast cancer in women at an earlier stage or what can be done to prevent cattle infected with mad cow disease from causing CJD in humans, or they can be more general problems like how to reduce the waiting lists for hospital treatment or how to improve the energy situation. The next step is to make a list of the relevant alternatives. It is important to include all relevant alternatives in order to come to a good solution. Ignorance, conventional thinking and lack of imagination can be limiting factors here. The third step consists of explaining possible consequences for every alternative. Some of these consequences are positive. This is the benefit (or utility). In the above examples the benefit in the first case would be that women with breast cancer would be treated at an earlier stage, in the second case it would prevent people from getting CJD, and in the third case more people would get treatment and care faster. However, not all the consequences are benefits. Some consequences represent possible harm, or costs. Normally each alternative represents both benefits and costs.

The fourth step consists of comparing the different alternatives. To start with we can say that the decisive question is whether the proposed intervention will have any effect at all. In the example concerning breast cancer we would ask the question whether for example mass screenings (for example an offer of yearly mammography exams to all women over thirty years old) would make it possible for us to detect breast cancer earlier, and further, whether an early diagnosis increases the chance for successful treatment.

The possible causal relation between BSE and CJD was addressed in an interesting report from December 2000 (Food Standard Agency 2000). As a point of departure the report accepts that there most likely is a causal connection between BSE and CJD, and recommends a series of interventions in order to prevent people from contracting CJD through eating meat from cattle with mad cow disease. It was recommended that animals over the age of 30 months should not be used in food production, and a prohibition against the use of meat from mammals in animal food. This will entail a great deal of expense.

Consequently the point is that every benefit must be weighed against the costs. However if the costs and benefits are to be compared, a value must be placed on them. Cost-benefit analyses fit directly into the utilitarian tradition in ethics from Jeremy Bentham and John Stuart Mill. Bentham maintained that happiness and utility may be regarded as equivalent to pleasure, which he in principle thought could be quantified. The morally correct alternative to act upon would be the one that seems to give more pleasure than pain. Bentham even compiled a list of criteria for the computation of the amount of desire, like the intensity of the sense impression, its purity, durability and so on. Later utilitarians, among others, John Stuart Mill, expanded the concept of utility.

In cost-benefit analyses costs and benefits are usually converted to monetary value. This is of course a serious limitation. Values that cannot be converted into monetary value therefore drop out of the analysis. For example it is easy to put a price on the benefit one gets from introducing efficiency measures in a hospital, however the reduction of patient care has no place in this mathematical problem. Attempts have been made to put a price on "soft values", like environmental damages, but this is problematic.

In the example with BSA and CJD the value of a human life is mentioned. But is it possible to put a price on a human life? If every person has an intrinsic value, it is impossible to represent it by a monetary value. However we need to be realistic here. Even in our affluent society there are many unsolved problems and the world in general does not show signs of abundance. Therefore, there will always be a problem of priority. If we place large resources into reducing the risk of damage in one area, we take resources that could have been used to save lives elsewhere. Therefore it is also impossible to have a risk-free society, and planners have to recognize that accidents will sometimes happen. The amount of resources that should be put in to the prevention accidents needs to be evaluated in relation to the costs. Trains are for example very safe modes of transportation. Nevertheless, railway accidents occur, either due to technical failure or human error, and some of these accidents involve the loss of human lives. One can of course try to reduce this risk, but somewhere there needs to be a limit. If the costs become too high, it will become impossible to use trains as modes of transport. Then other modes of transport will be used, which can have even greater accident rates.

The report on BSE and CJD has an important virtue: It is emphasized throughout the report that all the information about the topic is very uncertain, and that this must be taken into consideration in the conclusions. However it has not been the norm that one takes such reservations in cost-benefit analyses. If we look historically at the development of cost-benefit analyses, this becomes clearly evident. In the USA, The Army Corps of Engineers were the pioneers in the development of cost-benefit analyses from the 1920s on. They were used in large engineering projects, as in the regulation of rivers and the construction of power plants. The benefit/cost ratio was calculated for each project. If the value was greater than 1, the project was approved. For example, the project could be approved if the value was 1.035; there was never any talk about margin of error. The Congressional Committees never questioned the figures that were presented. Cost-benefit analyses were assumed to be the incarnation of rationality and objectivity. (Porter 1995: 156)

In a complex and uncertain world one can obtain apparent certainty by simplification and idealisation. That is why it is worth including the following quote as a reminder:

> Virtually all the formal treatments of risk and uncertainty in game theory, operations research, economics or management science require that the odds be known, that numbers be attachable to the probabilities and magnitudes of possible outcomes. In practice, since such numbers are rarely available, they are usually assumed or invented, the alternative being to admit that the formal treatments have nothing useful to say about the problem under discussion. (Adams 1995: 25-26)

I believe that this is at least part of the reason why both experts and non-experts have a tendency to underestimate error and uncertainty in cost-benefit analyses. (Cf. Kammen and Hassenzahl 1999: 126)

Recognizing uncertainty

The basic idea of risk assessment has been that chance can be "tamed" by using statistics. Therefore, the basic preference for the simple has not been changed. The physicist Per Bak tells a story to demonstrate how inadequate this way of thinking may be when it is applied to complex systems:

> The obsession among physicists to construct simplified models is well illustrated by the story about the theoretical physicist asked to help a farmer raise cows that would produce more milk. For a long time, nobody heard from him, but eventually he emerged from hiding, in a very excited state. "I now have figured it all out," he says, and proceeds to the blackboard with a piece of chalk and draws a circle. "Consider a spherical cow..." Here, unfortunately, it appears that universality does not apply. We have to deal with the real cow. (Bak 1997: 45)

This is a fictitious example, but there is an abundance of real-life examples. One is the deposit of radioactive waste that was constructed in Maxey Flats in Kentucky in 1962. Several scientists, from both industry and university, carried out risk assessment, and calculated that plutonium deposited at the site during a period of 24,000 years would penetrate less than one cm into the surrounding rock. The chances of the material spreading outside the site was estimated to be zero. But only 10 years after the waste had been deposited, Plutonium and other radioactive material were discovered at a distance of 3-4 kilometers from the dumping site. The geological calculations were erroneous with a factor of 10^6, that is to say a factor of one million. The reason for this being that the calculations had to be based on an idealized model. Experts confess that errors of this order of magnitude are not uncommon in risk assessments. For example, the official assessments of the risk of an accident in a nuclear power plant similar to the Three Mile Island accident deviate with two orders of magnitude, in other words a factor of one hundred. (Shrader-Frechett 1989: 53-54)

To see the general problem we have to introduce a few more distinctions. In addition to risk we have uncertainty and ignorance. When we have uncertainty, it means that we know what can go wrong. (When we also know the probabilities, we are talking about risk.) However, there are often situations where we have no idea of what can go wrong. These situations are characterized by ignorance. Ignorance means that we don't know what we don't know. In risk assessment it is desirable to reduce uncertainty to risk, because it enables the application of the mathematical methods of risk analysis (probability theory, statistics and the like). This requires simplification and idealization, either in the form of experiments or by applying mathematical models as described earlier. However, the fundamental problem is that the reduction of uncertainty often inevitably increases ignorance. (Wynne 1992: 114)

Silvio Funtowicz and Jerome Ravetz have constructed a figure that nicely illustrates the problem of uncertainty.

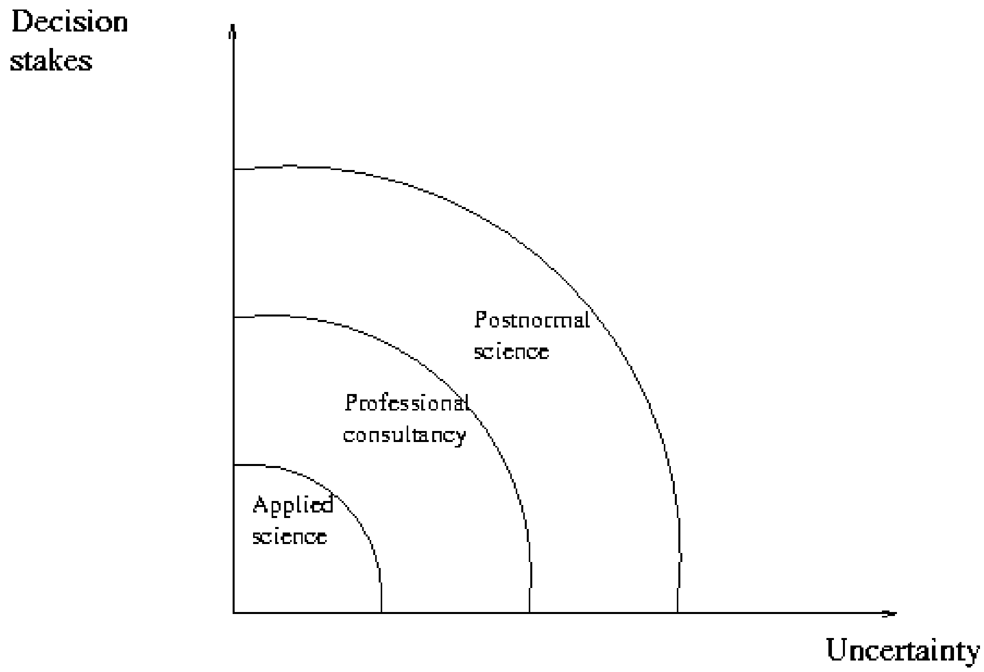

Figure 1
Slightly modified from Funtowicz and Ravetz (1993: 745)

The inner circle encompasses applied science. Here the uncertainty is low, and there is little at stake. This is the area of traditional scientific techniques, for example the use of statistics, risk calculations, and the like. Outside this we have what they call "professional consultancy". Here the uncertainty is larger, and decision stakes are higher. I believe the best example of this type of activity is a medical doctor working as general practitioner. The uncertainty in making a diagnosis is often large; at the same time decisions may be urgent. In these cases standard procedures for dealing with uncertainty can no more be applied. As an illustration we can take a patient who is suffering from heart disease. In the worst case scenario the disease is fatal, but it may also be the case that the patient can live for many years with the disease. There is however an operation that can cure the patient, but there is a certain risk that the patient dies during the operation. What should one choose? Only the patient himself can weigh the facts against value in this type of situation, and today we take it for granted that the patient should make the final decision.

The outer circle encompasses the area for "postnormal science" (This term alludes to Thomas Kuhn's "normal science"). Here the uncertainty is large, and at the same time decision stakes are high. Global warming is a typical example of a problem that falls under postnormal science. We have postnormal science when the facts are uncertain, values are up for discussion, decision stakes are high and decisions are urgent. Postnormal science has a few characteristics that may seem paradoxical. One of these is that we can have "weak facts" and "hard values". An example will be possible measures we can make to reduce the harmful effects of a rising sea level due to global warming. Some prognoses indicate that the sea level may rise. However, these prognoses are uncertain, and our knowledge of the possible effects of the countermeasures is equally uncertain. Therefore, the facts are "soft". But the values are "hard". There is no doubt that it would be a global disaster if many of the world's largest cities were flooded. (Funtowicz and Ravetz 1993: 750)

Perhaps Funtowicz's and Ravetz's most important contribution is the suggestion that non-experts should be involved in the decision making process in a much more radical way than today. Of course, they do not suggest that laypersons should for example take over the expert's role in the laboratory. Scientific expertise must be respected, however it must also find its place in a larger setting. Funtowicz and Ravetz use the expression "extended peer communities". This alludes to the traditional quality assurance of scientific knowledge by having manuscripts approved by experts in the field ("peer communities") before they are published. "Extended peer communities" means that this system is extended to include non-experts. There is no easy recipe for how this should be organised. Finding a good organisational form will certainly require some trial and error, and it is not realistic to believe that we will find one model that can be used in every single situation. I will in the following restrict myself to mentioning a couple of reasons why non-experts should be brought in.

I have previously discussed the uses of simple and idealised models in science, and I have pointed out that these can be a source of error when they are applied to complex systems. Here non-experts can give the necessary correction because they may be closer to the problems. They can for example have valuable knowledge of local climate changes or changes in the amount of fish that the experts do not have. Much of this knowledge is tacit. But we may have the opposite situation as well. Non-experts may see something the experts do not see because they are not so close to the problems as the experts. We know that experts can be victims of "tunnel vision": Their expertise narrows down their view so that they lose sight of the big picture.

I started this article by referring to Toulmin's theory of modernity. One of the basic ideas was that some important insights from Renaissance humanism were lost in the scientific revolution. However, according to Toulmin we are about to return to the situation of the Renaissance humanism. The process of humanizing modern science has already started, and Toulmin points to tendencies in contemporary science. His description of this process is similar to Funtowicz's and Ravetz's postnormal science. Basically, this process is a growing recognition of the limits of our own perspective, and the acceptance of uncertainty.

One of the tendencies is a change in the conception of objectivity. Modern science's ideal of objectivity left no place for ethical norms and values, and the result was the separation of "ought" from "is", and values from facts. Norms and values had to be justified outside the sciences (for example in religion, in a theory of human nature, or they might be regarded as mere conventions). Of course this did not prevent ethical norms and values from being relevant in the application of science. Today the scientific and technical development has precluded the separation between facts and values. One example is modern medicine. Previously, medical doctors could take it for granted that the goal of their activity was to save life. But when modern medicine enables us to extend the life processes beyond any realistic hope of regaining a meaningful life, this goal no more makes sense. According to Toulmin, the fact that the oxygen level in the patient's arterial blood is at a life threatening level, is on the same par as, for example, the fact that the patient does not want to be resuscitated by technical means. Another example is physics. The invention of the atomic bomb changed the consciousness of physicists. They understood that it is impossible to do physics without taking the wider, societal context, into consideration. Toulmin's third example is engineering. Previously any technical project would be carried out if it was technically feasible and useful in a narrow sense. Now it is unthinkable to initiate a technical project without taking a much broader set of factors into consideration.

Of course, just returning to the past is out of the question. We cannot, and we do not want to, ignore modern science and technology. The only possible alternative is to "humanize modernity" (Toulmin 1990: 180).

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