One of the most characteristic features of science is its systematic nature. This systematicity is reflected in the descriptions and explanations that science provides, as well as the ways that science establishes knowledge claims and expands and represents knowledge. This systematicity also has drawbacks and negative consequences. It leads to specialization, fragmentation and communication difficulties, and to the seductive but erroneous thought that science can provide solutions to all of society’s problems.

What is the nature of science? Of course, it is virtually impossible to answer this question in a short text. The scientific endeavour is just too complex. But sketching out some of the most salient features of scientific knowledge highlights one of the most distinctive characteristic features of science — its systematicity. This is not to say that other forms of knowledge are entirely unsystematic. For instance, if you want to know how many people are in some room, you would use a systematic procedure, namely counting, but this does not make you a scientist. However, scientific knowledge is typically more systematic than other forms of knowledge, and it expands its systematicity into new domains. The systematicity of scientific knowledge concerns more than one single aspect of science.

THE SYSTEMATICITY OF SCIENCE

In this short essay, the systematic character of scientific knowledge is examined with respect to five features of science: how science describes; how science explains; how science establishes knowledge claims; how science expands knowledge; and how science represents knowledge. These features of scientific knowledge are systematic in not exactly the same sense. But systematicity is always distinct from the purely accidental and random. Thus, my account of the nature of science will not really be an answer in terms of one single defining quality. Instead, the systematicity of science will concern all five of these features. Together, they articulate the specific nature of science, one of the most spectacular cultural achievements of humankind. In this essay, I will only deal with the natural sciences, but the analysis can easily be extended to cover the specific features of the social sciences and the humanities as well.

How science describes

Scientific descriptions represent a first aspect of the systematicity of scientific knowledge. In the historical natural sciences like cosmology, which describes the history of the universe, or paleontology which describes the history of life on Earth, descriptions of particular events and processes are predominant. For example, palaeontologists attempt to describe the particular chain of events which led to the extinction of the dinosaurs some 60 million years ago. With respect to these particular descriptions, the historical natural sciences share much with other historical disciplines such as political history or art history. However, in the laboratory sciences, such as solid state physics or protein chemistry, the situation is quite different. In these fields, scientists are not interested in a particular historical event or process, but always in groups of events or processes. Thus, while investigating a particular metal such as copper, scientists are not interested in the behaviour of the particular piece of metal in their hands. They are interested in the behaviour of every piece of copper, or perhaps even more generally, in all metals. In other words, in the laboratory sciences, scientists aim for general descriptions, that is, descriptions that provide generalizations about a certain domain of phenomena, or the regularities holding true in this domain. Making such general descriptions presupposes a classification appropriate to the respective phenomena. Similar phenomena must be grouped together, otherwise a generalized description is not possible. Here, we find the first aspect of the systematicity of science. Science classifies phenomena in a systematic fashion. The systematic scientific ordering, or classification, of phenomena is mirrored by the large number of scientific disciplines and sub-disciplines, each of which deals with a particular domain of phenomena. For these domains, science aims at generalized descriptions which express the common nature of the phenomena in that respective domain.

Why does science aim at generalized descriptions? The reasons are the same as in everyday life and in engineering. Generalized descriptions can be used
Error may arise as the result of mistakes,
false assumptions, entrenched traditions,
belief in authorities, superstition,
ishful thinking, prejudice, bias,
and even fraud.

Science is extremely careful
and successful in detecting
and eliminating all sorts
of error. It is not that
it is invariably successful, but
it is the most systematic
human enterprise in its attempt
to eliminate error in the search
for knowledge.

How science explains

Science typically creates theories. Theories serve many functions in science, and a complete description of all these functions is well beyond the limits of a short article. What is of main concern here is the explanatory, unifying, and predictive power of scientific theories. Typically, some domain of phenomena which is well described, but not really understood, finds an explanation through a scientific theory. Consider the planetary motions for which fairly accurate mathematical descriptions have been known for quite a long time. But explaining why these motions take place as they do is a different kind of story. In the history of science, extremely diverse explanations have been given for these motions. For a long time, the most successful one had been that given by Isaac Newton. Newton’s theory postulated a gravitational force as an explanatory device. This gravitational force is a typical ingredient of scientific theories as it is an entity that cannot be directly observed. In a sense, it is a speculative component of science. Because theories contain such speculative elements, they are risky, but I will return to this risk a little later. At this point, the systematic aspect of scientific theories is more important, namely their power to provide causal explanations which unify entire domains of phenomena. Thus, Newton’s gravitational theory explained and unified such diverse phenomena as the free fall of apples, the motion of planets, and the occurrence of the tides. It systematically structured a vast domain of apparently diverse phenomena by providing a unified, quantitative, causal explanation: all of these phenomena are caused by gravitation.

Furthermore, with the use of theories, the predictive power of science increases tremendously. For example, many cultures had discovered the regularities in the motions of celestial objects, including knowledge of the temporal pattern of eclipses. On the basis of these generalized descriptions, it was possible to predict eclipses of the sun and the moon. But once these regularities were explained by an appropriate theory of gravitation, additional novel predictions became feasible; for instance, the prediction of the existence of a previously unknown planet. On the basis of the twentieth century theory of gravitation, the general theory of relativity, even the existence of entirely novel entities has been predicted, among them black holes.

One particularly successful explanatory strategy is the use of reductionist explanations. Reductionist explanations make systematic use of the fact that, very often, the behaviour of a particular system can be explained with reference to its constituent parts together with the laws governing their interactions. Large areas of science such as solid state physics, or quantum chemistry, or molecular biology rely on this sort of explanation. However, this explanatory strategy is only successful under two conditions: if the system’s interaction with its environment can be neglected, and if the internal organization of the system is not exceedingly complex. Evidently, systems that interact strongly with their environment cannot be explained with recourse to their component parts alone. Instead, approaches are needed that take these interactions into account. Additionally, complex systems may exhibit behaviour that is unexpected on the basis of knowledge of their component parts. In these systems, reductionist explanations may reach practical, or even in principle, limits.

How science establishes knowledge claims

The third aspect of science which exhibits systematicity is probably one of the most popular features of science. Science purports to provide a form of knowledge that is particularly reliable and trustworthy. What is the basis of this claim? The central insight, which science takes extremely seriously, is that human knowledge is constantly threatened by error. Error may arise as the result of mistakes, false assumptions, entrenched traditions, belief in authorities, superstition, wishful thinking, prejudice, bias, and even fraud. Science is extremely careful and successful in detecting and eliminating all sorts of...
Although experiments have been performed in various contexts across many cultures, the systematic use of experiment, as a means to test and confirm knowledge claims, is a unique feature of modern science.

error. It is not that it is invariably successful, but it is the most systematic human enterprise in its attempt to eliminate error in the search for knowledge. Finding adequate generalized descriptions of some domain of phenomena is hard enough. It is all too easy to overgeneralize and fall prey to prejudices. But the real difficulty with error elimination concerns the fact that science strives for explanatory theories which contain entities that cannot be directly observed. How can the purely imagined be distinguished from an unobservable reality? How can science distinguish between a theory which uncovers some invisible mechanism that secretly governs some set of natural phenomena from a mere flight of fancy?

In this respect, the most outstanding characteristic feature of modern science is its use of experiment. Although experiments have been performed in various contexts across many cultures, the systematic use of experiment, as a means to test and confirm knowledge claims, is a unique feature of modern science. Of course, observation has been used by many other knowledge-seeking traditions, including the Western scholarly tradition out of which modern science emerged historically. But the systematic use of experiment to generate new knowledge and to test knowledge claims underwrites some of the outstanding features of modern science. First, the use of experiment allows scientists to test purported causal connections. Whereas by observing, one can only see a temporal succession of events, by experimenting, one can test whether the temporal succession is causal. Roughly speaking, this is accomplished by repeatedly producing one event and observing if the other event occurs thereafter. Second, experiments allow scientists to test claims about the existence and properties of postulated theoretical entities much more rigorously compared to observation alone. In an experiment, one can create a situation in which the postulated theoretical entities should behave in a particular manner. If these effects can indeed be observed, then one has indirect evidence for the existence and properties of the postulated entities. Finally, knowledge that has been experimentally tested can immediately be used practically. This is because applying knowledge technologically is basically the same series of physical actions as experimenting, but with different intentions. An experiment which tests a hypothesis about the causal connection between events A and B produces A and then observes whether B occurs. Technologies which apply knowledge about the causal connection between A and B produce A in order to generate the desired effect B. In this way, the experimental character of scientific knowledge lies at the heart of its technological fertility.

The intellectual integrity of science crucially depends upon its willingness to assess its knowledge claims systematically. In mathematics, the most rigorous of all sciences, no statement that expresses more than a convention is accepted, unless it is backed up by a proof. The natural sciences share a similar feature. Although one cannot prove statements from the natural sciences with mathematical certainty, no statement is accepted unless it is supported by a variety of empirical evidence, and no statement is immune to revision or even refutation in light of empirical evidence. Systematically discovering the strengths and weaknesses of particular knowledge claims is one of the hallmarks of science. Experiments also play a crucial role in generating new knowledge, which brings me to the fourth aspect of the systematicity of science.
those who are more familiar with the traditional idea that science proceeds by applying the scientific method — understood as a set of rules which guarantee reliability of scientific knowledge and its progress. During the last few decades, close scrutiny of science has led to a move away from the idea of the scientific method. The procedures of science appear much more individually case-based. Productive scientific work is largely fuelled by existing scientific results which it takes as models and then extends. Abstract rules or principles are not a major governing force. Science, especially fundamental science, is much more artful and playful than a strictly rule-governed procedure. Instead, the extension by analogy and metaphor from what is already known into unknown domains aids the creative process.

In addition, science exploits another body of knowledge in an extremely successful way. Science exploits technology. Of course, in the twentieth century, technology is largely science-based in the sense that many scientific results enter technological innovations. But it would be far from the truth to assume that technology is developed by a rather thoughtless, mechanical application of scientific results. On the contrary, engineers have their own creative traditions, quite distinct from the scientists'. But regardless of the extent to which a certain brand of technology is science-based, science is always eager to exploit the latest technology. This is because of science's systematic use of experiment which I mentioned earlier. The import of new technology into science provides a whole host of opportunities for constructing new experiments or building more precise measuring instruments. In the second half of the twentieth century, the use of computers and software has had innumerable applications in science. Completely new fields of research have emerged as the result of the possibility of electronic computing, and many existing fields have been thoroughly revolutionized in the process. Again, we see a positive feedback process between science and technology. Science is used to create new technologies, and new technologies are used to improve and extend scientific knowledge.

I have been talking about the intentional, planned expansion of scientific knowledge. But knowledge generation may also contain an element of chance, in particular with respect to surprising, novel knowledge. Paradoxically as it may sound, science is even systematic in exploiting chance for generating new insights. There are several aspects of this systematic use of chance. One aspect concerns so-called brute force approaches, where a vast number of cases are systematically searched, one by one, until an interesting case arises. An example is the search for pharmacologically active compounds by systematically examining a large number of chemical substances. A second way of forcing chance is by explorative experimentation into a comparatively unknown system. Bringing that system into different experimental conditions reveals its properties. A third way of exploiting chance for the generation of new knowledge is as a by-product of experiments which aim at testing
hypotheses. In these experiments, one has expectations about the outcome if the hypothesis is acceptable. Deviations from these expectations are readily noted. Such deviations may be due to the falsity of the hypothesis tested, but they may also be due to the falsity of some auxiliary hypothesis which was tacitly used, or even taken for granted, in the experimental set-up. In the latter case, quite unexpected discoveries - chance discoveries as they are sometimes called - may be made. Scientific research procedures are such that these chances have a good chance of being noticed.

**How science represents knowledge**

The last aspects of science's systematity that I will briefly discuss concerns the representation of scientific knowledge. The background idea is that knowledge itself is internally structured, and that an adequate representation of this knowledge must take this internal structure into account. The results of science can and must be represented in an orderly, systematic fashion. Once again, a prime example is mathematics in which the systematic representation of knowledge is pushed to its extreme. But in the empirical sciences, important distinctions also have to be made with respect to the representations of knowledge: the general has to be distinguished from the particular, the well-established from the merely hypothetical, the descriptive from the theoretical, the logically dependent from the logically independent, etc. It is quite clear that the systematicity in representation is instrumental for other aspects of the systematicity of science. The systematic representation of existing knowledge may reveal gaps, errors, or weaknesses of all sorts that might otherwise go unnoticed.

**Drawbacks**

Having reviewed those aspects which exhibit science's systematicity, let me now turn to those features that are, as a consequence of systematicity, drawbacks of science. There are two issues that seem to be most important in this context.

**Specialization and fragmentation**

The systematic character of scientific research leads to specialization. Specialization is an effect of systematically pursuing questions that present themselves in the course of research. Specialization is the price one has to pay for systematic, in-depth knowledge. There are also counter-tendencies in science that tend to overcome specialization. These tendencies are due to systematic attempts to unify science with the use of overarching theories, and by internally driven interdisciplinary research. But the main fact remains that scientific knowledge is quite fragmented due to specialization, at least in practice. There are various negative consequences of this kind of specialization and ensuing fragmentation. There is a communication problem between science and the public, between science and science policy; and within science between different disciplines, even between sub-disciplines in the same field. These communication difficulties give rise to a variety of problems. It is difficult for the public to understand what is going on in science; policy makers have difficulties setting priorities; interdisciplinary research poses special challenges; and so on.

**Over-extension of science**

A second negative consequence of the systematic and comprehensive character of science is the seductive thought that science really addresses everything. But there are limits to science. I do not mean this in the trivial sense that there are limited resources for science. Rather, we must be prepared to accept that there are essential problems which do not admit scientific solutions. In the century ahead, we will have to confront problems of drastically new proportions. Science will be an absolutely indispensable means for tackling the challenges ahead. But it would be unrealistic to expect that the solutions to all of our problems will be provided by science by itself. Instead, we will have to make decisions concerning priorities, concerning values, and concerning conflicting priorities and values - and this both at a local and global level. In short, we will have to make decisions that are essentially political, not scientific. For these decisions, science can only be of subsidiary help. Of course, there is no substitute for the kind of help science, including the social sciences, can provide, especially in predicting the probable consequences of our decisions and actions. But the decisions will be ours, and we will not be able to avoid painful responsibilities by delegating them to science.

**TO CONCLUDE**

Let me summarize this overview of the systematic character of science by quoting Albert Einstein, one of the greatest scientific minds of the twentieth century. He claimed: "The whole of science is nothing more than a refinement of everyday thinking." Replace "refinement" with "systematization" and you have the essence of this account.

**NOTES AND REFERENCES**

1. This paper is an adapted version of an invited keynote address presented by the author to the World Conference on Science in Budapest on 27 June 1999.

Paul Hoyningen-Huen is a theoretical physicist and a philosopher by training with special interests in the philosophy and ethics of science. In the 1980s, he spent a year both at the Massachusetts Institute of Technology (MIT) and at the Center for Philosophy of Science at the University of Pittsburgh. Until 1997, he was professor of philosophy at the University of Konstanz (Germany). He is currently Director of the Center for Philosophy and Ethics of Science, University of Hannover, Oelzenstrasse 9, 30169 Hannover, Germany. E-mail: hoyningen@inbox.xx.uni-hannover.de.