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Scientific Thinking

MY DAILY WORK consists mostly of research in mathematical physics, and I have often wondered about the intellectual processes that constitute this activity. How does a problem arise? How does it get solved? What is the nature of scientific thinking? Many people have asked these sorts of questions. Their answers fill many books and come under many labels: epistemology, cognitive science, neurophysiology, history of science, and so on. I have read a number of these books and have been in part gratified, in part disappointed. Clearly the questions I was asking are very difficult, and it appears that they cannot be fully answered at this time. I have, however, come to the notion that my insight into the nature of scientific thinking could be usefully complemented by analyzing my own way of working and that of my professional colleagues.

The idea is that scientific thinking is best understood by studying the good practice of science and in fact by being a scientist immersed in research work. This does not mean that popular beliefs of the research community should be accepted uncritically. I have, for example, serious reservations with regard to the mathematical Platonism professed by many mathematicians. But asking professionals how they work seems a better starting point than ideological views of how they should function.

Of course, asking yourself how you function is introspection, and introspection is notoriously unreliable. This is a very serious issue, and it will require that we be constantly alert: what are good and what are bad questions you may ask yourself? A physicist knows that trying to learn about the nature of time by introspection is pointless. But the same physicist will be willing to explain how he or she tries to solve certain kinds of problems (and this is also introspection). The distinction between acceptable and unacceptable questions is in many cases obvious to a working scientist and is really at the heart of the so-called scientific method, which has required centuries to develop. I would thus refrain from saying that the distinction between good and

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bad questions is always obvious, but I maintain that scientific training helps in making the distinction.

Enough for the moment about introspection. Let me state again that I have been led by curiosity about the intellectual processes of the scientist and in particular about my own work. As a result of my quest I have come to a certain number of views or ideas that I have first, naturally, discussed with colleagues.¹ Now I am putting these views and ideas in writing for a more general audience. Let me say right away that I have no final theory to propose. Rather, my main ambition is to give a detailed description of scientific thinking: it is a somewhat subtle and complex matter, and absolutely fascinating. To repeat: I shall discuss my views and ideas but avoid dogmatic assertions. Such assertions might give nonprofessionals the false impression that the relations between human intelligence and what we call *reality* have been clearly and finally elucidated. Also, a dogmatic attitude might encourage some professional colleagues to state as firm and final conclusions their own somewhat uncertain beliefs. We are in a domain where discussion is necessary and under way. But we have at this time informed opinions rather than certain knowledge.

After all these verbal precautions, let me state a conclusion that I find hard to escape: *the structure of human science is largely dependent on the special nature and organization of the human brain*. I am not at all suggesting here that an alien intelligent species might develop science with conclusions opposite to ours. Rather, I shall later argue that what our supposed alien intelligent species would understand (and be interested in) might be hard to translate into something that we would understand (and be interested in).

Here is another conclusion: *what we call the scientific method is a different thing in different disciplines*. This will hardly surprise those who have worked both in mathematics and in physics or in physics and in biology. The subject matter defines to some extent the rules of the game, which are different in different areas of science. Even different areas of mathematics (say, algebra and smooth dynamics) have a very different feel. I shall in what follows try to understand the *mathematician's brain*. This is not at all because I find mathematics more interesting than physics and biology. The point is that mathematics may be

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viewed as a production of the human mind limited only by the rules of pure logic. (This statement might have to be qualified later, but it is good enough for our present purposes.) Physics, by contrast, is also constrained by the physical reality of the world that surrounds us. (It may be difficult to define what we mean by physical reality, but it does very much constrain physical theory.) As for biology, it deals with a group of Earth-bound organisms that are all historically related: this is quite a serious constraint.

The two “conclusions” I have just proposed are of limited value because they are stated in such general and vague terms. What is interesting is to get into the details of how science is done and what it captures of the elusive nature of things. What I call the nature of things or the structure of reality is what science is about. That includes the logical structures studied by mathematics and the physical or biological structures of the world we live in. It would be counterproductive to try to define *reality* or *knowledge* at this point. But clearly there has been an immense progress in our knowledge of the nature of things over the past centuries or decades. I would go beyond that and claim a third conclusion: *what we call knowledge has changed with time*.

To explain what I mean, let me discuss the example of Isaac Newton.² His contributions to the creation of calculus, mechanics, and optics make him one of the greatest scientists of all time. But he has left many pages of notes telling us that he had other interests as well: he spent a lot of time doing alchemical manipulations and also trying to correlate history with the prophecies of the Old Testament.

Looking back at Newton’s work, we can readily see which part of it we want to call science: his calculus, mechanics, and optics had tremendous later developments. His alchemy and his study of prophecies by contrast did not lead anywhere. The lack of success of alchemy can be understood from the way of thinking of alchemists, which involved relations between the metals and the planets and other concepts that we consider to be without rational or empirical justification. As to the esoteric use of the Scriptures to understand history, it continues to this day, but most scientists *know* that this is nonsense (and this opinion is supported by statistical studies).³

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A modern scientist distinguishes readily between Newton's good science and his pseudoscientific endeavors. How is it that the same admirable mind that unveiled the secrets of celestial mechanics could completely go astray in other domains? The question is irritating because we see good science as honest and guided by reason while pseudoscience is often dishonest and intellectually off the track. But what track? What we see now as the well-marked path of science was at Newton's time an obscure track among other obscure tracks that probably led nowhere. The progress of science is not just that we have learned the solution of many problems but, perhaps more important, that we have changed the way we approach new problems.

We have thus gained new insight into what are good and bad questions and what are good and bad approaches to them. This change in perspective is a change in the nature of what we call *knowledge*. And this change of perspective gives a contemporary scientist, or an educated layman, some intellectual superiority over giants like Newton. By intellectual superiority I mean not just more knowledge and better methods but in fact a deeper grasp of the nature of things.