Paths of Discovery
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DIFFERENT TYPES OF DISCOVERY LESSONS FROM THE HISTORY OF SCIENCE

JÜRGEN MITTELSTRASS

What is known to science is known in different ways – a quick look at, for instance, textbooks in mathematics, physics, biology or economics or history renders this apparent. The same is true of the ways in which science acquires its knowledge. There are inductive, deductive, experimental and many other ways and methods. And its successes are documented in confirmed hypotheses, explanations of the hitherto inexplicable, and in discoveries.

It is above all the discoveries which represent the appeal of science – for the scientific layman as well as for the scientist. The new is revealed in discoveries, and the new is, by all means, the aim of scientific endeavours. Aiming at the discovery of the new, science develops its methods and structures and defines its concept of research. Thus, occasionally a distinction is made between hypothesis-driven and discovery-driven research, apparently thinking of the expected new in the former, and of the unexpected new in the latter case. But such a distinction is artificial. After all, hypothesis-driven research is also aimed at discovering the new, and discovery-driven research also requires methodic tools, parts of which are in turn hypotheses. Precisely this is what the history of science teaches, provided one conceives it not just as an arsenal of past insights and errors, but also as an expression of the scientific spirit, which recognises itself in past as well as present representations.

Not even science has a subscription to the new or a strategy for finding it routinely. There are many roads not just leading to Rome, but to new scientific insights as well – and, of course, many leading past them too. I shall describe in more detail three paths through which new insights have been found in the history of science, using short examples: (1) Discoveries which were surprising to science and the discoverers themselves, (2) discoveries which had been expected by the discoverer and science up to a point, but which were novel in their details, (3) discoveries which had been expected by the discoverer, but which came as a complete surprise to science.[1]

First, the discoveries which came as surprises to science and even to the discoverer himself, hence representing something unexpected and new. Two examples: (1) The first is very famous: the *discovery of the X-ray*. In November 1895, Röntgen was experimenting with a gas discharge tube, that is, an instrument that emits electrons (for instance, from a heated wire), and accelerates them by applying voltage; the tube itself is under vacuum, or at least, the gas pressure is significantly reduced. He covered the tube with cardboard paper to see to what extent it would still let light pass, and thus observed that some crystals, left lying on his desk for no particular reason, started to fluoresce. Röntgen discovered that this fluorescence must have been caused by a new sort of radiation, being emitted by the gas discharge tube, and apparently capable of covering great distances. This strikingly powerful radiation were X-rays, today well-known to us.

(2) Rutherford's *discovery of the atomic nucleus*. In 1909 Rutherford was doing an experiment to examine the structure of the atom, which was designed following military rules: If you don't know what the object in front of you is, then you'd better shoot at it.[2] Rutherford used a radioactive material as ray gun, and shot a narrow ray of alpha-particles on a thin metal sheet. Behind this sheet, a fluorescent screen had been mounted, which, when an alpha-particle hit it, would document this with a microscopic flash of light. The big surprise, now, was that the alpha-particles were not just observed as being slightly redirected after hitting the sheet, but that their direction was changed altogether. Some were even repelled by the sheet, as if they had hit a solid wall. Rutherford later observed:

> It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.[3]

[1] A comprehensive account of the development of the new in science may be found in: J. Mittelstrass, *Leonardo-Welt: Über Wissenschaft, Forschung und Verantwortung,* Frankfurt 1992, pp. 74-95 (I 4 'Die Wissenschaften und das Neue').

[2] See R.U. Sexl, *Was die Welt zusammenhält: Physik auf der Suche nach dem Bauplan der Natur*, Frankfurt and Berlin and Vienna 1984, p. 145.

[3] E. Rutherford, 'The Theory of Atomic Structure', in J. Needham and W. Pagel (eds.), *Background to Modern Science*. Ten Lectures at Cambridge Arranged by the History of Science Committee 1936 (Cambridge, 1938), p. 68.

Rutherford then tried to do justice to this 'incredible event' by developing his theory of the structure of the atomic nucleus. Some of the (positively charged) alpha-particles had directly hit the (also positively charged) atomic nuclei and were hence repelled by them in their initial direction of movement.

Such are the examples for the entirely unexpected discoveries. As examples of the discoveries which had been expected, to some extent, by the discoverer as well as by science in general, but which were novel in detail, let me present the following two: (1) Lavoisier's *discovery of the conjoined composite nature of water*. Lavoisier had, since 1778, been looking for the oxide (the compound with oxygen) of hydrogen, discovered in 1766 by Cavendish, but had not made any tangible progress. It was only in 1781, when Cavendish noticed (and Lavoisier learned of this in 1783), that in an explosion of so-called detonating gas, hydrogen and oxygen could be permuted into their own weight in water, that Lavoisier inferred that the long searched-for hydrogen-oxide was really water itself, and that hence water was not an elementary substance, but a compound. So, what was not surprising here was the existence of a hydrogen-oxide; entirely surprising was the discovery that this oxide was the well-known substance water.

(2) Örstedt's *discovery of electromagnetism*. In the natural philosophy of romanticism, all natural powers were thought of as expressions of a single and fundamental force, and this gave rise to the expectation that natural powers would have to be convertible into each other. In particular, this was thought to apply to electricity and magnetism. Under the influence of this idea, Örstedt searched for such a conversion and discovered, in 1820, more or less accidentally during a lecture, that a magnetic needle would be deflected by a wire lead conducting electricity. The connexion between electricity and magnetism was thus discovered. The novel and unexpected aspect of this effect, now consisted of the fact that the current would cause the magnetic needle to rotate. What had been looked for was a direct attraction or repulsion between the electric charge and the magnetic poles. What had not been expected was a circular magnetic field surrounding the conductor the current was flowing through. A mistaken background assumption had prevented the discovery of electromagnetism for a while; chance had to come to the rescue to lead to the right track.[4]

[4] See R.U. Sexl, *op. cit.*, pp. 61-62. For a diverging account see J. Agassi, *Towards an Historiography of Science* (The Hague, 1963), pp. 67-74. Agassi assumes that the discovery was less accidental than traditionally thought.

Finally, two examples of discoveries which had been expected by the discoverer, but came as complete surprises to science: (1) Poisson's *white spot*. In about 1830 Fresnel presented the first complete version of a wave theory of light. The heart of this theory was the assumption that waves of light are of a transversal nature (that is, they occur perpendicularly to the direction of extension propagation). Poisson thought this theory to be wholly absurd, and to prove this, he deduced an apparently nonsensical consequence from it. According to Fresnel's theory, a white spot would have to occur at the midpoint of the shadow produced by a point-shaped source of light directed at a circular disc ('Poisson's white spot'). Arago then undertook the (to all appearances, redundant) labour to also demonstrate the falsity of this consequence experimentally. But, entirely surprisingly, he really did find the predicted spot. Although he was not the originator of the theory who predicted this novel effect, he could have done so, had he executed the deduction. In the case of a theoretical prediction of a novel effect, its empirical manifestation might surprise the general public, but not the theorist.

(2) Einstein's *prediction of the diversion deflection of light in the gravitational field*. Einstein had deduced, from the General Theory of Relativity, that light would be deflected from its initial trajectory by a certain angle by a gravitational field. In 1919, Eddington examined the position of stars, the light of which was passing the sun very closely. He then compared these positions with those of the same stars at the time these were more distant from the sun. Indeed, the predicted deflection was observed in the precise degree expected. This successful theoretical prediction was greeted with great surprise by the uninitiated. At the same time, the process of testing the General Theory of Relativity has been compared to the Catholic procedure of canonization ('November 6, 1919, the day on which Einstein was canonized').[5] The successful prediction of the deflection of light was one of the required miracles.

These examples teach that there is no simple way to arrive at the new in science, and that the diverse ways to arrive at the new are not simple. Furthermore, they are only rarely due to the strict following of scientific programmes, and this is why talk of scientific revolutions, which has again become popular with Thomas Kuhn's work in the history of science, is not that misguided. Indeed, scientific revolutions differ from political and

[5] A. Pais, *'Subtle is the Lord ...': The Science and the Life of Albert Einstein*, (Oxford and New York, 1982), p. 305.

social ones by having a much more varied potential for change, and, as a rule, for producing fewer losses, but, after all, this is not a disadvantage and not deplorable. Moreover, theories in science sometimes die more honourably than on the political or ideological stage. There, they often only come to an end with the biological end of their adherents – it is true, although this is not altogether unknown in science too.[6]

Science, in its search for the scientific new, does not just get driven by discoveries, accidental or non-accidental ones – one could express this by striding from truth to truth – but, surprisingly, also via errors, in a heuristic sense.[7] Let me give you a final example also for this heuristic fruitfulness of errors, Einstein's *derivation of the General Theory of Relativity*. This relied on principles which were partially motivated epistemologically. One of the principles pertinent and even essential for the formulation of the theory is *Mach's Principle*, as Einstein calls it. According to the ideas of Newton, there is one prime, indeed, truly immobile, system of reference, 'absolute space'; movements relative to absolute space are indicated by the presence of forces of inertia (for instance, centrifugal forces). Through such forces, accordingly, absolute space takes effect on the objects, while, at the same time, the objects are never able to disturb absolute space in its tranquil existence. Einstein considered the assumption of a uni-directional causation for inconsistence and instead assumed that the forces of inertia are explicable through the relative positions and movements of the bodies (an idea he attributed to Mach).

Mach's principle is not just one of the central motives for the development of the General Theory of Relativity, but also plays an important role in the process of formulating the theory. However, it turns out that the fully developed theory does not satisfy Mach's principle. That is, the theory allows space-time structures as physically possible, in which forces of inertia originate out of an overarching space-time that is independent of objects and their movements – even if this does not have the Newtonian shape of an absolutely immovable space. Furthermore, according to our current empirical knowledge, we may assume that in our universe, one such space-

[6] See M. Planck, *Wissenschaftliche Selbstbiographie* (Leipzig, 1948), p. 22 ('A new scientific truth does not usually become accepted by having its opponents convinced and having them declare their new conviction, but mostly by its opponents dying out, and having the new generation getting acquainted with the truth straightaway').

[7] Compare the more comprehensive account in J. Mittelstrass, *Die Häuser des Wissens: Wissenschaftstheoretische Studien* (Frankfurt, 1998), pp. 13-28 (I 1 'Vom Nutzen des Irrtums in der Wissenschaft').

time structure contradicting Mach's principle has been realised. Hence, Mach's principle would be false; following today's theoretical and empirical state of knowledge, our universe is equipped with a space-time structure that is in part independent of the mass-energy distribution bodies in the universe. Nevertheless, as I have explained, Mach's principle played an essential and probable indispensable role in the process of formulating the General Theory of Relativity. At least, the development of the theory would not have been possible along the path taken by Einstein without assuming this principle.

In other words, error too may play an essential role, not just not hindering scientific progress, but even furthering it. The 'game of science' (Popper) knows many successful moves; one of these is the truth of error.