Characteristics of the Scientific Method

Bertrand Russell

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Scientific method has been often described, and it is not possible, at this date, to say anything very new about it. Nevertheless, it is necessary to describe it if we are to be in a position later to consider whether any other method of acquiring general knowledge exists.

In arriving at a scientific law there are three main stages: the first consists in observing the **significant** facts; the second in arriving at a hypothesis, which, if it is true, would account for these facts; the third in deducing from this hypothesis consequences which can be tested by observation. If the consequences are **verified**, the hypothesis is **provisionally** accepted as true, although it will usually require modification later on as the result of the discovery of further facts.

In the existing state of science, no facts and no hypotheses are isolated; they exist within the general body of scientific knowledge. The **significance** of a fact is relative to such knowledge. To say that a fact is significant in science, is to say that it helps to establish or **refute** some general law; for science, though it starts from observation of the particular, is not concerned essentially with the particular, but with the general. A fact, in science, is not a mere fact, but an **instance**. In this, the scientist differs from the artist, who, if he **deigns** to notice facts at all, is likely to notice them in all their particularity. Science, in its ultimate ideal, consists of a set of **propositions** arranged in a **hierarchy**, the lowest level of the hierarchy being concerned with particular facts, and the highest with some general law, governing everything in the universe. The various levels in the hierarchy have a twofold logical connection, traveling one up, one down; the upward connection proceeds by **induction**, the downward by **deduction**. That is to say, in a perfected science, we should proceed as follows: the particular facts, A, B, C, D, etc., suggest as probable a certain general law, of which, if it is true, they are all instances. Another set of facts suggests another general law, and so on. All these general laws suggest, by induction, a law of a higher order of generality of which, if it is true, they are instances. There will be many such stages in passing from the particular facts observed to the most general law as yet **ascertained**. From this general law we proceed in turn deductively, until we arrive at the particular facts from which our previous induction had started. In textbooks the deductive order will be adopted, but in the laboratory the inductive order. …

Throughout the history of physics, the importance of the *significant* fact has been very **evident**. The facts that are significant at any one stage in the development of a theory are quite different from those that are significant at another stage. The **essential** thing is always to look for such facts as illustrate one law in isolation or at any rate, only in combination with laws whose effects are well known. This is why experiment plays such an important part in scientific discovery. In an experiment the circumstances are artificially simplified, so that some one law in isolation may become observable. In most **concrete** situations, what actually happens requires for its explanation a number of laws of nature, but in order to discover these one by one it is usually necessary to invent circumstances such that only one of them is relevant. Moreover, the most instructive phenomena may be very difficult to observe. …

Although this may seem a paradox, all exact science is dominated by the idea of **approximation**. When a man tells you that he knows the exact truth about anything, you are safe in inferring that he is an inexact man. Every careful measurement in science is always given with the probable error which is a technical term, conveying a precise meaning. It means: that amount of error, which is just as likely to be greater than the actual error as to be less. It is characteristic of those matters in which something is known with exceptional accuracy that, in them, every observer admits that he is likely to be wrong, and knows about how much wrong he is likely to be. In matters where the truth is not ascertainable, no one admits that there is the slightest possibility of even the **minutest** error in his opinions. … It is an odd fact that **subjective certainty is inversely proportional to objective certainty**. The less reason a man has to suppose himself in the right, the more **vehemently** he asserts that there is no doubt whatever that he is exactly right. … No man who has the scientific temper asserts that what is now believed in science is exactly right; he asserts that it is a stage on the road to towards the exact truth. When a change occurs in science, as, for example, from Newton's law of gravitation to Einstein's, what had been done is not overthrown, but is replaced by something slightly more accurate. Suppose you measure yourself with a rough apparatus, and came to the conclusion that you were 6 ft. tall. You would not suppose, if you were wise, that your height was exactly 6 ft., but rather that your height was (say) between 5 ft. 11 in. and 6 ft. 1 in. Further, if a very careful measurement showed that your height was (within a tenth of an inch) 5ft. 11 9/10 in., you would not consider that that had overthrown the previous result. The previous result was that your height was *about* 6ft., and this remains true. The case with the changes in science is precisely **analogous**.

The part played by measurement and quantity in science is very great, but is, I think, sometimes overestimated. Mathematical technique is powerful, and men of science are naturally anxious to be able to apply it whenever possible; but a law may be quite scientific without being **quantitative**. Pavlov's laws concerning conditioned reflexes may serve as an illustration. … We must, therefore, in dealing with such a matter as animal behavior, be content in the meantime with **qualitative** laws, which are none the less scientific for not being quantitative.

One advantage of quantitative **precision**, where it is possible, is that it gives much greater strength to inductive arguments. Suppose, for example, that you invent a hypothesis, according to which a certain observable quantity should have a **magnitude** which you work out to five significant figures; and suppose you then find by observation that the quantity in question has this magnitude. You will feel that such a **coincidence** between theory and observation can hardly be an accident, and that your theory must contain at least some important element of truth. Experience shows, however, that it is easy to attach too much importance to such coincidences. … The truth is, that men cannot frame sufficiently abstract hypotheses; imagination is always intruding upon logic, and causing men to make pictures of occurrences which are essentially incapable of being visualized. … The world that we can picture is the world that we see; but the world of physics is an abstract world that cannot be seen. For this reason, even a hypothesis which accounts with a minute exactitude for all known relevant facts must not be regarded as certainly true, since it is probably only some highly abstract aspect of the hypothesis that is logically necessary in the deductions which we make from it to observable **phenomena**.

All scientific laws rest upon induction, which, considered as a logical process, is open to doubt, and not capable of given certainty. Speaking **crudely**, an inductive argument is of the following kind. If a certain hypothesis is true, then such and such facts will be observable; now these facts are observable; therefore, the hypothesis is probably true. An argument of this sort will have varying degrees of validity according to circumstances. If we could prove that no other hypothesis was compatible with the observed facts, we could arrive at certainty, but this is hardly ever possible. In general, there will be no method of thinking of all the possible hypotheses, or, if there is, it will be found that more than one of them is compatible with the facts. When this is the case, the scientist adopts the simplest as a working hypothesis, and only reverts to more complicated hypotheses if new facts show that the simplest hypothesis is inadequate. If you have never seen a cat without a tail, the simplest hypothesis to account for this fact would be: "all cats have tails"; but the first time you saw a Manx cat, you would be compelled to adopt a more complicated hypothesis. The man who argues that because all cats he has seen have tails, therefore all cats have tails, is employing what is called "induction by simple **enumeration**." This is a very dangerous form of argument. In its better forms, induction is based upon the fact that our hypothesis leads to consequences which are found to be true, but which, if they had not been observed, would seem extremely improbable. If you meet a man who has a pair of dice that always throw sevens, it is possible that he is lucky; but there is another hypothesis which would make the observed facts less astonishing. You will, therefore, be well advised to adopt this other hypothesis. In all good inductions, the facts accounted for by the hypothesis are such as would be antecedently improbably, and the more improbably they would be, the greater becomes the probability of the hypothesis which accounts for them. This, as we remarked a moment ago, is one of the advantages of measurement. If something, which might have any size, is found to have just the size that your hypothesis had led you to expect, you feel that your hypothesis must at least have something in it. As common sense, this seems evident, but as logic, it has certain difficulties. This, however, we will not consider (here). …

There is one remaining characteristic of scientific method about which something must be said, namely, analysis. It is generally assumed by men of science, at any rate as working hypothesis, that any concrete occurrence is the result of a number of causes, each of which, acting separately, might produce some different result from that which actually occurs; and that the resultant can be calculated when the effects of the separate causes are known. … The principle that causal laws can be separated, and then recombined, is in some degree essential to the procedure of science, for it is impossible to take account of everything at once, or to arrive at causal laws unless we can isolate them one at a time. It must be said, however, that there is no ***a priori*** reason to suppose that the effects of two causes, acting simultaneously, will be calculable from the effects which they have severally and in the most modern physics, this principle is found to have less truth than was formerly supposed. It remains a practical and approximate principle in suitable circumstances, but it cannot be laid down as a general property of the universe. Undoubtedly, where it fails, science becomes very difficult; but, so far as can be seen at present, it retains sufficient truth to be employed as a hypothesis, except in the most advanced and delicate calculations.