Popper, Kuhn and How do we get Laws and Theories in Science?

Part-1

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We normally look to Science when we want explanations for any natural phenomenon. The hall-mark of Science lies in looking for cause and effect relations, explanations for these phenomena. By the end of this article, I hope you will be able to appreciate the nature of Science as an endeavour that tries to find explanations for the things and processes that we see around us. These explanations are only accepted when they have been tested several times against nature (that is, by carrying out different kinds of studies and experiments) by several people. Hence, scientific knowledge is accorded the status of tested knowledge and we can place great confidence in its predictions.

Cause-effect relations in phenomena and processes around us:

Our species name is *Homo sapiens* which means 'thinking man' (where 'man' is to be read as human beings – people were not always gender-sensitive), and since recorded history, we know that people have been asking questions about various phenomena and explanations at various levels have always been given. And we can safely assume that human beings must have had this trait during the long period of our evolution before we started writing down things too.

So we have always had questions ranging from the meaning of existence to why the sky is blue, why we fall sick, how birds migrate, why fire burns, to why we die. The earliest attempts to answer these questions led to organised religions as we know them today and our myths and legends explain everything from lightning to eclipses. But a different approach to answering at least a particular set of problems grew into the present discipline of Science.

Why is Science different from other human endeavours, especially religion? There are two major points of difference; one is regarding subject matter – religion doesn't restrict itself and has answers for all kinds of questions – even ethics and morals while Science limits itself to the natural world and tries to find explanations for certain phenomena only. The other difference is that Science does not accept any kind of authority and any claim made can always be checked by anyone using accepted methods and following the accepted rules of logic. Religion, on the other hand, is generally made up of teachings which are either revealed to the founder or that of a person that we accept as the 'guru' and generally these teachings cannot be questioned, only elaborated upon.

So we come to the understanding of Science as a discipline that tries to give explanations for various natural phenomena and tries to find the root cause for various on-going processes that we see around us. And this effort is generally understood to have western roots, but if we study history, we can see the contributions of the Indian, Chinese and Arab civilizations to the growth of modern Science over the last 400-600 years. For example, the history of the use of the magnetic compass tells us how far the Chinese mariners were in their understanding of the phenomenon of magnetism and that they had even accurately recorded the inclination of the magnetic needle in relation to the latitude. Similarly, there is a manuscript in Patna in the Khuda Baksh Library which gives the derivation of the laws of reflection and refraction by an Arab scientist centuries before these were studied in the West (though today we only study Snell's law and of the contributions made by Newton). Hence, we see that the same kind of questions arose in different places and logical investigation led to the same kind of understandings the world over.

The most important identifying feature of this discipline of Science is the methodology and logic used to investigate the processes that interest us and the manner of cause-effect relationships that are established. That is, we try to identify the effect of various factors or what the underlying cause behind any change would be. We shall look at these points in greater detail, especially the method of Science and the type of logic used in Science in this unit. We shall also try to understand why Science never claims to give ultimate answers.

The Ever-Changing Concepts in Science:

We were talking of the differences between religion and Science in the earlier section. In religion, the teachings remain the same and don't change over centuries even while the nature of knowledge in Science is always accepted as tentative. Why is this? The state of accepted knowledge in Science changes not only with an improvement in techniques, but also with progress in other, and often unrelated, areas. For example, information about the internal organisation in cells grew with the invention of the compound microscope as well as a better understanding of what different stains were doing to the cell organelles. Leuwenhoek was working with a simple microscope, but he managed to get very good results because he managed to grind excellent lenses for himself. But by the end of the 19th century, the extreme limit of the magnification using light microscope had been achieved. Further refinements were possible with the use of the ultracentrifuge to separate different cell components and study them, but the next major leap came with the introduction of the electron microscope when we got to see the internal structure of various organelles too in great detail.

[Here insert two illustrations – one of a cell under a light microscope (compound) which shows mitochondria too and another of an electron microscope or scanning tunnel microscope picture of a mitochondrion showing the internal structure.]

So if we were to list what was known about the cell at different times over the last few centuries since Robert Hooke first described it in 1665, we see that the knowledge has been steadily increasing and also that the nature of this knowledge has been changing too. This kind of incremental change in our knowledge is true of any topic that we take up. And our understanding is also continuously getting refined. We can take up some more examples to understand this better.

When Dalton propounded the atomic theory in 1808, he visualised the atoms as solid, elastic spheres. Then we got an inkling of the internal structure of the atom, that it was made up of still more fundamental particles and the growth of this understanding can be seen when we consider sequentially Thomson's model of the atom (plum-pudding model), Rutherford's model of the atom (solar system model), Bohr's model (with fixed energy levels) and finally the quantum-mechanical model of the atom. And the number of fundamental particles has also been increasing.

Similarly, if we look at how living organisms have been classified at different times, we see our understanding of these living organisms being reflected in how they were classified. Aristotle classified animals as those that live in the sea, sky and land. So he ended up classifying whales and fish together and similarly birds and bats were also placed together. Later when we studied the anatomy of different animals, we kept all animals with backbones in one group and further divided them on the basis of features like whether they have feathers, or scales, or hair, or nothing as their outer covering. Under this classification, it was thought that both birds and mammals had evolved from reptiles. But recent studies using genes to look at how closely related different animals are has revealed something surprising – birds are said to have evolved from dinosaurs, in fact, they are so closely related that birds are said to be modern-day dinosaurs, that is, dinosaurs are not extinct after all!!! Similarly, it was thought that all fishes were more closely related to each other than they were to the rest of the vertebrates. But now it is known that bony fishes (like sardines (**some examples of local fishes could be given, I don't know any**)) are closer in evolutionary terms to amphibians, reptiles, birds and mammals than they are to fishes which have a skeleton made of cartilage like sharks.

So, while it wouldn't be fair to say that the Science of yesteryears was wrong, it is definitely wrong to say that the Science of today is final. We don't know what on-going research is going to reveal or what pet theories are going to be overthrown. At the same time, while accepting that our knowledge today is not the ultimate truth, what we know today is consistent, that is, what is known from different fields of study do not contradict each other and the accepted theories have given us replicable and reliable results. Hence, we can base our present decisions on today's state of knowledge while accepting the fact that everything that we know today is forever open to question. It is the current research which reveals the gaps in our knowledge and shows us new avenues to explore leading to the development of new knowledge.

Sometimes when new facts come to light because of fresh research, we learn something new or we end up with a new theory of how certain events are to be explained. At other times, it is a revolutionary new theory that leads to a search that results in new facts. For example, Einstein's theory explained the effect of gravity by postulating that massive bodies caused the curvature of space around them. And if space itself were to be curved, then light traveling through this space could not be going in a straight line. This bending of light was dramatically demonstrated by Eddington who managed to photograph the apparent position of stars behind or close to the Sun during a solar eclipse in 1919. Einstein's theory found greater acceptance after these facts / observations were seen to support it.

This means that Science is a constantly evolving body of knowledge, and does not ever claim to have attained the ultimate truth. Being good at Science or being a good student of Science does not mean knowing a whole lot of things, but knowing how one can check out a whole lot of things or find out about things or even think of creative ways to solve or explain problems.

The validity of scientific claims – falsification as a test:

In the last section, we saw how ideas and theories in Science keep changing. So how are we to judge whether any theory or fact is acceptable, even if it is only by the state of knowledge at that particular point in time? This question of the certainty of our knowledge has always vexed people and this is true for all subjects, not just Science. How do we know that the sum of three angles of a triangle is 180º or that Rana Pratap took part in a battle in Haldi Ghat? Of course, the method of gathering and verifying knowledge depends on the nature of the subject and the justifications given in Science will be different from that of Maths and History. So in this section, we shall try and understand how we know what we know in Science and by what means the justification is done. In my last article (**give issue no and pages here?**), I had described the process of deduction (used widely in mathematics) and induction in some detail, so I shall not do so again over here. This article will go a bit more deeper into the issues that surround the nature and reliability of scientific knowledge.

What philosophers have always loved about deduction is the absolute certainty of the conclusion – given that the major and minor premises are true, there can be no doubt about the validity of the conclusion. For example, in plane geometry, given Euclid's five postulates, we can prove a large number of theorems. But note that these theorems that you learn in school are true only given that the postulates are true. And the postulates are true only for plane geometry, that is, on a plane. If you were to draw a triangle on a sphere, the sum of angles would be more than 180º and this gives rise to spherical geometry with a different set of postulates (consider the triangle drawn by the 0º longitude at Greenwich, the 90º longitude and the equator as its three sides, what would be the sum of the angles in this triangle?!).

As we saw in the earlier article, it was long supposed that scientific knowledge is arrived at by a process of induction. As an example of induction in action, you observe that:

Iron conducts electricity.
Copper conducts electricity.
Gold conducts electricity.
Mercury conducts electricity.

And after you have observed scores of metals, you generalise that:

All metals conduct electricity.

Obviously, this means that you are willing to take a gamble that the metals that are yet to be studied or even discovered will also conduct electricity.

This process of making observations – many observations, under various conditions and then arriving at a generalisation was taken to be the process of establishing any new scientific knowledge and this process of induction was given the same status and accorded the same certainty as that of deduction. And the general perception of the method of Science is also understood to involve the process of induction only.

But, at the same time, a weakness in this process of induction was also recognised. This was that even a single counter-example could jeopardise the status of a generalisation. But we continue to accept the validity of generalisations even though we know that all of these have been established on the basis of a limited number of observations.

David Hume's Take on Induction:

David Hume was a philosopher who underlined the failings of the process of induction with maximum vigour. While accepting that this was the method used to establish scientific knowledge, he was merciless in pointing out the shortcomings of this logic. Firstly, he pointed out that any knowledge established by induction would always be tentative because one never knows when a counter observation is going to come along. Secondly, he pointed out that not only was this knowledge tentative, it was also of a very shaky philosophical basis. Unlike deductive knowledge which was certain, the process of induction offers no certainty, just a false sense of confidence because of familiarity with the process of generalisation. Since we have been making generalisations childhood onwards, we have a misplaced confidence that the next generalisation that we make will also be proved right. Thus, Hume pointed out the hollowness of inductive claims.

Therefore, after Hume, for a long time, people struggled to establish the veracity of scientific claims and place them on a sound philosophical footing. It was generally accepted that induction was the method of Science, but the image of Science had taken a beating because it seems as if scientific truths were as shaky as any other knowledge claims.

Popper's take on the method and nature of Science:

The most forceful defence of the privileged nature of scientific knowledge was made by Karl Popper. He was the first one to give an effective answer to Hume's challenge to the process of induction in establishing scientific knowledge and he did this by claiming that Science did not use the method of induction at all!

How did Popper come to this conclusion? Firstly, he said that the main problem was to differentiate scientific claims from other claims. And he said Science was a superior form of knowledge because scientific claims were testable and he said this in a novel manner when he said that scientific claims are falsifiable. This can be understood in the sense that any statement / theory / hypothesis that claims to be scientific also suggests a test which could potentially prove the above claim to be wrong. Popper said that this is the main point of demarcation between Science and other knowledge claims. It might be possible that the test might not be immediately possible either because the event predicted was far in the future, or because the necessary technology has not been developed. But in the long run, the ramifications of any hypothesis or theory would suggest a test where the theory could be disproved if adverse results came in.

Let us consider this by looking at a couple of examples. Before Lavoisier elucidated the role of oxygen in combustion and gave us the modern understanding, it was widely that the heat and light produced during combustion was due to a product called phlogiston which was released when things burned. So substances were said to have more or less of phlogiston in them depending on whether more or less heat and light was produced when that substance was burned. Now, when reactions began to be studied quantitatively, phlogiston turned out to be a hard substance to pin down. Sometimes the products of a reaction were seen to weigh more than the reactants and sometimes less; and accordingly positive or negative weights were attributed to phlogiston. (This actually happened because the role of gases in reactions were not known – either as reactants or as products. So, apparently a candle burned away giving out phlogiston in the form of heat and light because the products – water vapour and carbon dioxide – were not collected or recognised.) So in Popper's terms, the concept of phlogiston was not 'falsifiable' because no test could be devised to prove or disprove its existence, hence the phlogiston theory was not scientific.

On the other hand, when Einstein made the claim that massive bodies would cause space to curve, a test was suggested – that the light coming from stars behind the Sun could be seen to bend because the Sun was causing the space around it to be curved so that light would travel along this curve instead of in a straight line. Hence, Einstein's theory was falsifiable because if the light coming from the stars behind the Sun was not seen to bend, then the theory would be proved wrong. As mentioned earlier, this test was carried out during a solar eclipse in 1919 by Eddington and Einstein's theory found wide acceptance only after this.

Hence, what Popper was saying was that Science did not add to knowledge by inductive generalisations, but sought for underlying explanations for visible phenomena and these underlying explanations or hypotheses had to be testable. If the expected results were not obtained, then one had to come up with an alternate hypothesis. That is, the hypothesis gave an explanation for a certain phenomenon, this explanation led to a prediction about what would be observed under given conditions – that is, certain deductions were made following from the premises of the hypothesis. Hence, Popper said that Science did not use the method of induction, rather its method was that of hypothetico-deduction.

Further, to counter the ghost of Hume about the certainty of scientific knowledge, he said that while each scientific hypothesis had to propose a test that could disprove it, positive results did not *prove* the hypothesis, it just established the hypothesis as being more likely to be correct than before. So he said that scientific claims were always tentative, if more and more tests turned out to be giving positive results, this just gave greater *verisimilitude* to the hypothesis or theory, it was never proved to be *true*.

Therefore, the vision that Popper gave us about the nature of the scientific endeavour was one in which scientists proposed hypotheses and then set about trying to disprove them. This process resulted in a new, improved scientific theory which in turn was subjected to all kinds of trials. This image has found wide acceptance amongst the scientific community and it was felt that Popper had got to the root of the nature and process of Science.

However, Popper's ideas did not gain universal approval. One of the first to put forth objections was Thomas Kuhn. Kuhn had studied the history of Science and this history seemed to show that far from setting out to disprove each theory placed before them, what scientists tended to do was protect the theory by proposing extenuating circumstances – that is, they try to find limits for the applicability of the theory. And contrary results never led to a theory being abandoned. Rather, the scientific community stuck to a theory till a new theory came to replace it.

Kuhn called these major theories that guided scientific research a paradigm. A new theory meant an overthrow of the old paradigm and the establishment of a new paradigm. So far, his take might seem unexceptional. But Kuhn went on to claim that there were no rational reasons behind the paradigm shift, that scientists did not accept a new theory because it gave better results than the old theory, but because of social reasons. So the scientific community as a whole came to a decision based on *non-scientific* reasons about what paradigm was to be currently accepted to guide scientific research. They had to reach a consensus in such a manner, without depending on proof because Kuhn claimed that different paradigms were *incommensurable*. That is, they could not be compared on the basis of facts because, according to Kuhn, the facts themselves were different in different paradigms, and people belonging to different paradigms did not even share a common vocabulary to talk to each other and explain their own stand to the other person.

This statement sounds strange at first, so let me try and illustrate this with an example. Going back to how both Newton's theory and Einstein's theory both give explanations for the earth going around the Sun, let us look at this in a bit more detail. According to Newton, any body with any *mass* produces a gravitational field which affects other bodies with *mass*. It is this field or force of attraction between two bodies like the Sun and the earth which causes the earth to go around the Sun (which is the more massive body). According to Einstein, bodies with *mass* cause space to curve causing not just other bodies, but also light to move along this curved space; and in the case of the earth and the Sun, the Sun is so massive that it causes the earth to revolve around it. Now comes the punch-line, according to Kuhn, *mass* as described by Newton's theory was not the same as the *mass* that Einstein talked about. So any data produced was coloured by the theory, that is, the paradigm decides the very *facts* that people recorded. In other words, facts were *theory-laden*. So observations made under one paradigm could not be used to support or disprove some other paradigm. Come to think of it, these statements still sound very strange!!

Kuhn's ideas were hailed by social scientists and others because it was seen to attack the supremacy of Science; and a large amount of research has been done to understand how theories come to gain acceptance, and why some theories are never considered. Not surprisingly, scientists prefer to think of themselves according to Popper's image of the nature of Science where new theories are accepted because they gave better results, that is, explained more phenomena, than the older theory.

But before we throw out Kuhn's ideas since they are not very complimentary to Science, let us underline a couple of valid points he made, which show that Popper's undiluted ideas are not very sound. For one thing, contrary to Popper's claims, scientists do not reject a theory the minute some uncomfortable facts come along. In fact, they never reject a theory till a better theory comes along to replace it. Secondly, theory does influence our observations, especially what we think worthy of recording and what we ignore as unimportant.

Let us first look at how not rejecting a theory helps us learn new things. Galileo had discovered Jupiter's moons in 1610 and observed that their orbits around the parent planet led to their frequent eclipses when they went behind Jupiter, that is when Jupiter was between the earth and these satellites. (Jupiter's moons appeared as tiny dots on either side of the parent planet and then when their revolution around Jupiter caused them to go behind Jupiter, they would appear to move closer and closer to the planet's disc, and then disappear. After some time, they would reappear on the other side of the planet.) Further observations led him to think that these events were periodic and could be used in navigation (accurate measurement of time was a major problem while sailing the seas since it was one way to fix one's position, the story of how an accurate clock was invented is very interesting in itself, but will not be gone into here). Hence, predicting these events became important, but unexpected discrepancies kept coming up. Ole Romer, a Danish astronomer, instead of giving up on Galileo's theory, figured out that the differences in the times expected and observed were because light traveled at a finite speed and the relative positions of the earth and Jupiter in their respective orbits around the Sun meant that the light from Jupiter's satellites had to travel different distances before being observed. Thus, in 1676, he not only calculated the speed of light, but also predicted a 10-minute difference in the time when the next eclipse would be observed. If Romer had rejected the theory because the facts did not fit, what could he then have worked with, and we would also have had to wait for some other theory to help us measure the speed of light!

On to theory-laden observations. This comes from some personal experiences. There is a famous candle experiment, you light a candle, place it in a shallow plate containing water and then cover the candle with a beaker or a glass. You are aware of what is going to happen, so I shall not go into what observations are made. In fact, when we do this activity with teachers who know what is supposed to happen, they come up with a limited number of observations, they only report what they think is relevant. But when we do this with students, then the number of observations, the tiny details that they note is amazing. Here, with the teachers, the theory they have in their head seems to be filtering what they think should be observed / reported. Similarly, while conducting the activity of the effect of various solutions on litmus paper, I know very well that soap is a mild base, so the change in the colour of red litmus will be less than the intense blue that a solution of sodium hydroxide would produce, but people, whether children or adults who do the activity for the first time are often not very confident about soap being basic. There are many similar stories from the history of Science where things were ignored since they were not considered significant. So it is difficult to refute Kuhn's claim that what we observe depends on what theory we are aligned with. But whether this means that one theory is incommensurate with another is open to debate.

Anyway, if we accept Popper's view of the hypothetico-deductive nature of scientific knowledge, how do we arrive at laws or generalisations that require a theory or theories to explain them? The next section looks at how Science has refined techniques we use everyday to arrive at laws.