Chapter 1

Basic Concepts in the Philosophy of Science

The objective of science is to find out the character, properties, and the laws governing the various things and phenomena that we see in the natural world. Scientific research concerns the act of knowing what mankind does not know yet. And science follows very definite methods in trying to know what is yet unknown.

In the past various approaches have been proposed for finding out the answers to the questions we have about various events and things. Some of these have proved to be useful, and some have led people astray. Finally, after much trial and error, after much groping in the dark, after many successes and failures, science has found the proper methodological approach to find truth about nature. This is what constitutes the philosophy of science.

A scientist always has a philosophical outlook in approaching any problem. If the philosophical outlook is correct, he or she has a higher probability of finding success in his or her scientific pursuit. If the philosophical outlook is wrong, much labour may go in vein as he or she may proceed labouriously in the wrong direction. That is why it is important for a budding scientist to learn and adopt the correct philosophical outlook to guide his or her scientific pursuit.

In this chapter we shall deal with these issues related to the theory of knowledge.

1.1 What is science?

Science is mankind's attempt to find out truth about nature. We see, hear, feel things and events in nature with our five senses, and ask questions like "how did it happen?", "why does it happen?" etc. Then we seek answers to such questions. Science is a systematic way of seeking the answers.

In the ancient times also people had such questions in mind and did look for the answers. But the method of seeking answers were not clear at that time. As a result, people made wrong guesses, wrong ideas were propagated and were believed by people. Through millennia of human history, we slowly developed the *method* of seeking answers to the questions. This book will essentially tell you about this method.

It all starts with the experiences that we have as we go through our lives. Through our five senses, we get impressions about the external world. We perceive the world around us. And then we form questions about it.

The starting point, however, cannot be individual experiences, because these could be illusory. Individuals can have illusions, hallucinations, and many other forms of incorrect perception of external reality. The starting point, therefore, has to be collective experience — what many people experience and where their perceptions match. Individuals sometimes claim to have seen ghosts, but two persons have never seen the same ghost at the same time. That is why science does not ask questions about ghosts.

The creation of knowledge is a collective and cumulative process, created through transpersonalization of experience. When personal perceptions transcend the personal boundaries and are shared by a collective of people, that creates the condition of generation of conception. Conceptualization then creates condition for generation of knowledge. Such knowledge, created through collective experience, needs to be organised, crystallised, and systematised in order to be useful for mankind. Thus, systematic description and classification of natural objects and processes is another important function of science.

After having systematised and classified natural objects and processes, science proceeds through a series of abstractions—often with recourse to mathematics—to formulate the *principles and laws* that govern the character of natural objects and phenomena. In doing so, scientists formulate hypotheses and postulates, and then test them. We shall deal with the details of these methodological issues in the later chapters.

Note that science does not just ask questions about the character, function, and history of natural objects; it also asks the same questions about society. In that sense social science subjects like sociology, economics, history, politics, linguistics, etc. are very much part of science — because social sciences employ the same methods in seeking answers to its questions. One difference, however, is that in arts, literature, and such subjects there is emphasis on subjective imagination and romanticization—which are absent in science. In arts there is emphasis on value judgements (what is good, what is bad, etc.), while science bases itself on *truth judgements*.

1.2 The nature of truth

We have said earlier that science is mankind's attempt to find out truth about nature. And in this quest, many wrong ideas and illusions also arise, along with correct ideas. The effort of conscious science is to weed out the wrong ideas to reach truth.

But what is truth? Truth is correspondence between ideas and objective reality. When an idea can explain an objective phenomenon and can predict outcomes of experiments that are tested, we say that the idea reflects truth.

Such correspondence between ideas and reality is never reached in one shot, as individual thinking of a scientist that miraculously comes out to be absolutely correct. The correspondence between ideas and reality is gradually established, in small steps, with contributions from many scientists.

At any stage the correspondence is partial and incomplete. The idea may not correspond to the nature of the object being investigated in all respects; some factors in the objective reality may be explained by the idea and there may be some factors that are not taken into account in formulating the idea.

Can we make statements that are absolutely true? Of course we can: for example, "people cannot live without eating". Or "the sum of angles in a triangle drawn on a flat sheet of paper is 180°". But science does just not deal with assertions of such well known facts. It has to venture into things that are yet unknown. That why in science, most of the statements we make may be true in certain domains, true enough for certain purposes, but may not reflect absolute truth. They require to be continuously checked, modified, and corrected. When a new experience or knowledge makes its appearance, we may need to take fresh look at ideas earlier formulated and may have to re-state these altogether.

Newton's theory was tested on the motion of thousands of terrestrial bodies, experimental objects and planets. In all cases it came out successful. Yet, when the motion of the planet Mercury was accurately measured, it was found that its perihelion shift does not match the prediction of Newton's Laws. A completely new understanding of the phenomenon of gravitation—the general theory of relativity—was required to explain it.

The laws of classical mechanics and the laws of electromagnetism were also tested on thousands of situations. These had never failed. Yet, when people tried to apply the same laws to subatomic particles, these simply did not work. Completely new laws—the laws of quantum mechanics—were required to account for such situations.

The lesson we learn from this is that the test of a theory can never be completed, to be able to pronounce it to be true beyond any doubt. We have to continue to subject a hypothesis or a postulate to test from different angles, under different situations. It may pass some of the tests, fail in some others. Thus we come to know about the domain of applicability of each law of nature that we discover.

This continuous testing and check of what we believe to be true is a hallmark of science. Scientists have to develop the habit of doubting every established concept. Because we doubt, we question established theories, we test them again and again from different angles, and if we find a hole in our knowledge, new science is born from there. That is why a characteristic feature of science is *organised scepticism*.

Do we pronounce a theory that has failed in some test as 'wrong'? Do we say Newton's theory of gravitation is 'wrong'? No, because it did work in most situations. It worked because it provides a good 'model' of gravitation applicable for such situations. It is just that it does not encompass all situations, e.g., that of intense gravitational fields. For moderate gravitational fields, as prevails in most parts of the solar system, it provides a quite accurate description of nature. The character of most natural laws is like that.

That is why, even though the natural laws discovered by science reflect character of objective processes and phenomena, science does not claim them to be absolutely true. In fact, science has no interest in absolute truths—because if such an absolute truth is attained in any subject, there would be no room for further enquiry.

Moreover, science now realizes that nothing in the world is eternal. Everything is transient, everything goes through changes. If everything is mutable, constantly undergoing changes, it is obvious that truths about them also have to undergo changes. That is why science has given up the pursuit of absolute truths.

We now understand that truth is *relative* to the condition in space and time in which they are stated. The fact that the sum of angles in a triangle is 180° is true only in flat 'Euclidean' space.

The sum of angles in a triangle drawn on a football is *not* 180°. Thus, a statement that is true under one condition may be false under another.

The whole science of chemistry would make no sense in the conditions prevailing in the sun, because molecules cannot form under such conditions. The whole science of biology would make no sense in a planet devoid of life. They are true relative to the conditions prevailing on Earth.

Yet, truth is always *concrete* in the sense that the condition under which a theory has been tested and found to be true, remains true under that concrete condition. Even though Newtonian mechanics has been found to be inadequate in describing motion of bodies under intense gravity or inside atoms, it still remains true under the concrete conditions prevailing in the everyday world. Engineers still use Newtonian mechanics to build bridges or to design rockets for missions to Mars.

1.3 Subjective versus objective

Man is by nature inquisitive. He has questions about the things and events around him. But the way to seek answers to the questions is not the same today as it was in ancient times.

In ancient times there were reasonably well developed civilisations in India, China, Babylon, Egypt, Greece, Rome, and other places. The people of these civilisations also faced questions about things and events. Why is the sky blue? Why are the leaves green? Why does the sun rise in the East and set in the West? What happens when a man dies? How did the Earth come into being? Natural questions like these must have been faced by people of those civilisations.

1.3.1 Subjective thinking

In the ancient times the way to seek answers to such questions was through personal realisation. A person would think and would arrive at an answer. For him, that would be the answer to that question. Another person, thinking about the same question, might arrive at a different answer. Thus, for every question, there would be many answers.

Some people would not bother to think up answers on their own, and would trust the wisdom of some 'wise man'. Whatever answer that man provided, would be believed by his followers. Thus, there would be schools of thought, each with sets of followers.

An important characteristic feature of thinking of that time was that nobody would bother to check if an answer was right or wrong. The concept of verifying the correctness of ideas had not developed at that time.

This line of thinking, where a person—the subject—develops theories, concepts and ideas purely through personal realisation, is called *subjective thinking*.

Aristotle was a great thinker of the ancient times. He also faced questions regarding the things and phenomena around him and tried to answer them.

For example, he faced the question: Why do things move? He saw that a cart moves because a horse pulls it. By reflecting on this question and by generalising the above observation, he reached the conclusion: Force produces motion. He did not bother to check if this was indeed true.

He faced the question: If we drop a heavy body and a light body, which one will fall faster? He pondered over this question and came to the conclusion that the heavier body will fall faster. He did not check if his conclusion was correct. In fact, nobody bothered to check this for almost two thousand years, because the idea that such conclusions need to be checked had not yet appeared in the society. People just trusted the wisdom of Aristotle for generations. In fact, peoples' blind trust for ancient wisdom is a very dangerous thing: it prevents people from checking the correctness of conclusions reached in ancient times.

Aristotle wrote a book on human anatomy. In a chapter of the book, he writes that human males have 32 teeth, but females have 31. Where did he get these numbers? By thinking, and personal realisation—because in those times it was believed that women are inferior to men! He did not bother to count.

This is the character of subjective thinking.

If such errors were committed by one of the greatest minds of the ancient times, one can easily imagine how many wrong ideas were generated in the ancient times that needed to be corrected later. That is why science conscientiously avoids subjective mode of thinking.

1.3.2 Objective thinking

This mode of thinking continued all through the Greek and Roman periods and through the dark age in Europe, and began to be questioned at the onset of Renaissance. Galileo Galilei, a professor at the University of Pisa, was teaching mechanics, in which the Aristotelian ideas prevailed. But instead of blindly following what was written in the books, he said “let us test it”. As per legend, he took his students to the leaning tower of Pisa and dropped a large and a small piece of rock. To everyone’s surprise, they came down together and hit the ground with a single ‘thud’. He thus showed that a heavy body does not really fall faster than a light body.

Subsequently he subjected the other ideas of Aristotle to test by experimenting with balls rolling down inclined planes, and showed that force does not produce motion. He showed that force produces *change in motion*. He thus laid the foundation of modern mechanics.

More importantly, Galileo introduced a completely different way of thinking which said “My personal thinking, beliefs, and ideas may be wrong. I have to test these against objective reality to check if these are really true.” All ideas must be tested, and the sure way of doing so is through observation and experimentation on objects in nature. The ‘object’ should tell whether my ideas are right or wrong. This mode of thinking is called *objective thinking*.

Science has developed wholly by following the objective mode of thinking. In fact, the introduction of the objective mode of thinking is identified as the time of onset of the 'Scientific Age'.

Does that mean there was no science before Galileo? Does that mean nobody arrived at correct ideas through personal realisation? Such conclusions would be one-sided. Leucippus and Democritus in ancient Greece and Kanada in ancient India argued that everything is made of minute particles that are not further divisible. This was a rudimentary form of atomic theory, which saw further development in the hands of John Dalton in the 19th century. Kanada, Leucippus, and Democritus reached their conclusion through personal thinking, and hence their method was subjective. Even though they did not reach the same theory as did Dalton, it is undeniable that their ideas were much advanced in comparison to the ideas prevailing in their time.

The point therefore is that the ideas generated in ancient times need to be tested objectively, and if any idea stands the test, it should be recognised as an achievement. But today we cannot do science following subjective mode of thinking.

1.4 Materialism and idealism

Since the ancient times up to the modern era, there have been two major schools of thought in philosophy. All trends of philosophy can be categorised in either this or that of these two major schools of thought: materialism and idealism. These have been in struggle with each other since antiquity till the modern times.

Materialism says that nature is composed of matter, and that there is nothing but matter in this material world. Idealism says that there are supra-matter things and phenomena: soul, ghosts, magical powers, miracles—that are not subject to natural laws and cannot be probed by science. Materialism denies the existence of such entities and says that there is nothing supra-matter in this material world.

Both the schools of though recognise the importance of idea.

But idealism says that idea is prior, matter is secondary. Some idealists recognise something called 'primordial idea' out of which everything is born. Some idealists deny the existence of matter altogether and maintain that matter exists only in our idea. A cloth is red because we perceive it as red: it is recorded as red in our idea. There is no inherent 'redness' in the cloth; a piece of matter is what we perceive it to be. That is why, according to them, idea is prior.

Materialists, on the other hand, hold that matter is primary and idea is secondary. Idea is created in the human brain, which is a product of matter. And how are the ideas created? By interaction of the brain—which is a piece of matter—with the surrounding nature and society, which are also composed of matter. Therefore, the materialists hold, idea is a product of matter, and hence matter is primary.

More importantly, materialists assert that matter exists independent of our consciousness. Matter had existed before the conscious animal, man, evolved on this planet. Matter will continue to exist if humanity, due to some reason, gets exterminated. The form, character, and properties of matter, and the laws governing their interactions do not depend our consciousness.

In contrast, idealists hold that matter exists *in* our consciousness.

At this point the term 'matter' needs to be explained. The philosophical concept of matter is a bit different from what we find in some textbooks. The latter categorise matter as something that has mass, and in that sense distinguishes between matter and radiation. In philosophy, however, the concept of matter is arrived at through a process of generalisation. Such generalisation and abstraction is actually quite common. We see apples, bananas, peach, orange, etc., which are quite different from each other. But we abstract out the commonness in them and leave out the differences, to arrive at the concept of 'fruit'. In a similar way, we see deer, tiger, dog, cat, mouse—which are quite different from each other, but we can obtain the concept of 'mammal' by leaving out their differences and by focusing on the common features. In nature we see millions of things with different properties, but if we leave out their differences, we find that the only common feature is that they all *exist* independent of our consciousness. This is what is categorised by the philosophical term 'matter'. Thus, matter is anything that exists independent of our consciousness. In that sense electromagnetic radiation is also philosophically categorised as matter.

But how do we know something really exists? We know, because they leave some imprint on our senses. We *see* a dog, hence it exists. We *feel* the air, hence air exists. Two different people can see the same dog and can conclude that the dog exists (hence it does not depend on individual consciousness).

What about micro-organisms? True, we do not see or feel them. But we can do so with the aid of a microscope. Similarly we can see distant stars with the aid of telescopes. These are also matter, because we do perceive them with the aid of instruments. But there may be minute particles or distant astronomical objects that we do not see even with modern gadgets. Fifty or hundred years later we may be able to see them. This consideration has led to the concept that matter are things that exist independent of our consciousness, and which has the ability of making some imprint on our senses either directly or through sensitive instruments.

With this concept of matter, materialism says that there is nothing supra-matter in this material world, while idealism says that there is.

Science has been built based on materialism. That is why a basic position of science is that what we are investigating exist independent of our consciousness. The task of science is to form appropriate questions about such elements of objective reality and to bring the properties and laws governing them to our consciousness.

1.5 Falsifiability

In science we often think of proposing a theory and then testing if it is true. But the Austrian philosopher Karl Popper asked: Can we really test the correctness of the theory?

We have seen in Section 1.2 that Newton's theory was tested and found to be correct in hundreds of experiments; and yet was finally shown to be inadequate in dealing with intense gravity. The laws of classical mechanics was also tested and found to be correct, and yet was finally shown to be inadequate in dealing with subatomic particles. This tells us that we cannot really test a theory and pronounce it to be true.

If we can never be sure if a theory is absolutely right, if we have to continue to test theories without end, what does science stand on? Popper said, it should stand on its ability to reject wrong ideas. If many ideas are proposed to explain a situation and if all these ideas can be tested and the wrong ones can be identified and declared as 'false', then we do make progress in narrowing down the search for the correct idea.

Thus came the idea that every hypothesis, every postulate, every theory has to have the character that it should in principle be possible to identify it as false if it is really so. There should be the possibility that the outcome of an experiment or observation may contradict the expectation from the theory. If such an event is really observed, the theory can be declared as false.

More important is the demand that every modern theory should, in principle, be falsifiable. This does not mean that the theory has to be false. It has to be *falsifiable*, which means that the proposer of the theory has to clearly spell out which outcome of an experiment or observation would falsify the theory.

For example, the Big Bang theory says that the whole universe was created through an explosion from an infinitely dense object about 15×10^9 years ago. An obvious falsifiability criterion of this theory is that there should be no object in the universe older than the time of the Big Bang. If any object is found anywhere in the universe which must have existed for a longer time, or a structure whose formation must have taken more than 15 billion years, then the Big Bang theory is definitely false.

Suppose one proposes the hypothesis that the disease malaria is caused by specific species of bacteria transmitted by mosquitoes. What is its falsifiability criterion? Notice that the statement has two components: (a) that the disease is caused by a specific type of bacteria, and (b) that it is transmitted by mosquitoes. If a malaria affected person's blood is tested and that specific bacteria are not found, statement (a) is definitely false. If one lives in a place completely devoid of mosquitoes and yet develops the disease, statement (b) is definitely false. These are the falsifiability criteria of the statement.

But if one says that a person is afflicted by the disease due to a sin committed in the previous life, you would notice that the statement is not falsifiable. You cannot conceive any test or observation with which you can check if the statement is false. Same is true for all claims of supernatural powers, miracles, etc. Science would simply ignore all such statements, claims, and beliefs that are not falsifiable.

That is why, one has to formulate falsifiability criteria for any hypothesis or postulate that one proposes. One has to clearly state it in the paper, so that other scientists can test the hypothesis on the basis of that criterion. Without that, scientists do not take any hypothesis or theory seriously.

This is what Einstein meant when he said "No amount of experimentation can ever prove me right; a single experiment can prove me wrong."

1.6 Reproducibility

As a major demand on any theoretical proposition is falsifiability, a major demand on any experimental result is reprodicibility. This demand comes from objectivity. Any objective phenomenon should not depend on personal observation, interpretation or judgement. If a particular phenomenon is reported by a scientist, hundreds of other scientists will repeat the experiment, will create the same conditions under which the phenomenon was reported, and will check if the phenomenon really occurs. If the reported observation is not reproduced, it will not be accepted by the scientific community.

A scientist is not allowed to say that the phenomenon in question occurred in his/her lab alone, and may not occur in other labs. He or she cannot say that it could be observed because of his or her experimental expertise and that others do not possess similar expertise. The scientist has to report, in full detail, all the conditions under which the experiment was performed, so that anyone anywhere in the world can repeat the experiment. And a hard requirement is that the results should be reproducible if the same conditions are produced.

1.7 Causality

Causality is one of the central doctrines in science. Much of science bases itself on the premise that nothing happens without a cause. Scientists look for the reason behind every event. When an apple falls from a tree, they ask why did it come down? When they see the moon moving around the Earth, they ask why does it do so? When they see someone ill, they look for the reason behind the disease. All such investigations start from a question that the scientist forms in his mind, and the question mostly concerns the *cause* of various things we see around us.

Even though causality is such a crucial issue in science, it has been subject to intense controversy among scientists and philosophers on the question of what constitutes a cause for an event. Both the definition of 'cause', and the way of knowing whether A and B are causally linked have changed significantly over time.

The idea that there is a cause for every event was based on man's day-to-day experience, and naturally the initial formation of the idea took place in early human society. In fact, all human actions are based on some understanding of causal relationship. Eating rotten food *causes* disease, and so consume only fresh food. Snake bites *cause* death, and so keep away from snakes. The little seed *causes* the tree of the future, and so you plant the seed where you want the tree to be. Such mundane day-to-day actions of man also depended on some rudimentary concept of causality.

As far as we know, the idea first took a well articulated and concrete form in ancient Greece, especially in the writings of the prominent Greek philosopher Aristotle. He defined four types of causes behind every event: material cause, formal cause, efficient cause, and final cause.

To take an example, consider a marble sculpture, and ask what is the cause behind it? Aristotle says that the cause can be searched in four different ways. First, it is made of a specific type of white stone, marble. The sculpture would be impossible if the marble were not there. Therefore the material, marble, is a cause — the *material cause*. Second, the sculpture has a form, and the sculptor had that *form* in mind when he worked on the stone. The form that the sculptor had in mind is the *formal cause*. Third, the sculptor himself must be considered a cause because he acted in order to produce the sculpture. This is called the *efficient cause*. The purpose for which the sculpture is made, the ultimate objective for the sake of which the sculpture exists, is the *final cause*.

Through the middle ages, Aristotle's ideas held sway and the above concept of causality was almost universally accepted. During this period the idea of final cause assumed primacy over the others as the Church doctrine saw divine hand as the 'final cause' behind everything that happens.

During the Renaissance, scientists like Copernicus, Bruno, Galileo, and others started investigating nature afresh, and started looking at causal connections. Naturally the concept of causality came under scrutiny. In the writings of Galileo we see rejection of the idea of final cause. But we do not see any detailed treatise on the subject from scientists of that period.

In the 18th century, the Scottish philosopher David Hume (1711-1776) offered a full discourse on the problem of causality in his famous book *A Treatise of Human Nature*. According to Hume, two events *A* and *B* can be said to be causally connected if they satisfy three criteria:

- *Precedence*: *A* must precede *B* in time;
- *Contiguity*: *A* and *B* must not be widely separated in space and time;
- *Constant conjunction*: *A* and *B* always occur together.

By freeing the notion of causality from religious connotations and by making it testable, Hume made an enormous contribution to the advancement of human thought. Yet, his definition of causality had important flaws that were pointed out soon after his book was published.

For example, one could erroneously conclude 'day causes night,' because the occurrence of day and night follow all the criteria set by Hume. The eminent German philosopher Immanuel Kant pointed out another flaw: If a lead ball rests on a cushion and makes a dent, it is clear that the dent is caused by the pressure of the ball. Yet, the resting of the ball and appearance of the dent occurs simultaneously, not one after the other. So it was realised that one should say "an effect cannot precede the cause", not "the cause precedes the effect".

The necessity of contiguity is obvious in most cases: the cause of an event should be found close to where the event happens. But the tides in the coastal areas are caused by a distant object—the moon—and hence the cause is not contiguous with the effect in space. The criterion of constant conjunction also has similar problems. It is known that quinine cures malaria. Yet, if you administer quinine to a hundred malaria patients, 95 may recover and 5 may not. If we were to follow Hume's criterion of constant conjunction, we could not conclude that quinine causes cure of malaria. Statistical methods were developed later to address this problem, so that causal connection can be inferred even where conjunction is not 'constant'. This will be covered in a later chapter of this book.

Hume had also argued that the notion of causality is a mental construct: Humans observe certain sequence of events repeatedly, and notice that certain events occur in contiguity, succession, and constant conjunction. This experience leads the mind to make a 'customary transition' from the cause to the effect following inductive logic. Immanuel Kant (1724-1804) contradicted this position and asserted that we observe certain regularities in nature and construct causal connections, because such connections actually exist in nature. The principle of causality is required for the mind to make sense of the fact that certain sequence of events always obey a specific order in time.

John Stuart Mill (1806-1873) then focused on the problems of actually determining causal connections. He proposed four general methods on the basis of which experiments or planned observations can be designed for establishing causation:

1. *The method of concomitant variation*: Whenever A varies, if B varies in some particular manner (that is, if A goes up B always goes up or always goes down), then A is either a cause or an effect of B, or is connected with it through some fact of causation.

2. *The method of agreement*: If two or more instances of a phenomenon under investigation have only one factor in common, the factor in which alone all the instances agree, is the cause (or effect) of the given phenomenon.

3. *The method of difference*: If an instance in which the phenomenon B occurs and an instance in which it does not occur, have every circumstance in common except one (say, A), then A is the cause, or an indispensable part of the cause of B;

4. *The method of residues*: Suppose a phenomenon A has many aspects (say, P, Q, R, and S) and through previous research it is known what can cause P, Q, and S. Therefore the residue in the phenomenon is R. Now, in the condition prevailing immediately before the occurrence of A, if there is some aspect which is known to be not a causative agent of P, Q, and S, then it may be the cause of R. Thus, the method is to subduct from any phenomena such part as is known by previous induction to be the effect of certain antecedents, and the residue of the phenomena is the effect of the remaining antecedents.

I will now give examples from the history of science to show how such methods of finding causation have been used productively in making seminal discoveries.

In 1826 Georg Ohm found that when a voltage is applied on a piece of wire, current flows through it. He applied a variable voltage on a piece of wire and measured the current flowing through it. He found that when the voltage goes up, the current also goes up, and the two follow a linear relation—thus establishing the causal connection: the application of voltage *causes* the flow of current. Here he used the method of concomitant variation.

Notice that this does not imply a one-way causal connection. If one passes current through the piece of wire, a voltage appears across it, and these also follow a linear relationship. Thus, the current could also be the cause and voltage the effect.

In 1895, Wilhelm Conrad Roentgen announced the discovery of X-ray, which immediately caught the attention of the French chemist Becquerel. He suspected that this was related to the phenomenon of phosphorescence, where some materials glow in the dark after absorbing energy from the sun during daytime. As a test, he exposed a phosphorescent material, potassium uranyl sulphate, in the sun, and then covered it with black paper and put it on a photographic plate. The plate, when developed, turned black. It revealed silhouettes of the mineral samples, and, in subsequent experiments, the image of a coin or metal cutout interposed between the crystal and paper wrapping.

The next few days were cloudy, and so Becquerel put the whole contraption in his drawer. A week later, when the sun came back, he intended to resume his experiment. But instead of putting the potassium uranyl sulphate out in the sun, he first developed one of the photographic plates. Surprise: It turned black, meaning that it has been exposed to radiation even though the material had not absorbed sunlight. The discovery was serendipitous, but the importance of such chance factors can be grasped only by a trained mind. Becquerel did systematic investigation for a few months under different conditions—sometimes exposing the substance to sunlight and sometimes not exposing it—and looked for any difference in its ability to affect the silver compound in the photographic emulsion. He found no difference.

Here he conducted the experiment following the method of agreement. He deliberately created different conditions, and the only aspect in which the conditions agreed was the existence of potassium uranyl sulphate. Since the result was the same, he concluded that the *material* was the cause of the radiation, i.e., it was emitting the rays all by itself.

Around that time Marie Curie had completed her master's and was looking for a problem to work for her PhD. She decided to ask the question 'what causes radioactivity?' At that time it was only known that potassium uranyl sulphate is a source of radioactivity. But was it a property of the compound or that of the elements in it?

Curie did a series of experiments by taking different compounds of potassium, uranium, and sulphur. He noticed that such compounds do not have radioactivity unless uranium is present in it. Here she was using the method of difference, that led her to suspect that the element uranium is is cause of radioactivity.

In order to ascertain this conclusion, she took different compounds of uranium and measured the extent of radioactivity in each case. Thus she was adopting the method of concomitant variation. She found that the compounds that have a higher proportion of uranium showed a proportionately higher strength of radioactivity. This led her to conclude that the element uranium.

Madame Curie then asked the question: Is radioactivity a property of only the element uranium, or do other elements have the same property? She took various compounds that contain different elements and measured the radioactivity of each. In some cases the compounds showed radioactivity, and in some cases it didn't. She found that all the other conditions being the same, radiation is observed in presence of two metals—uranium and thorium. Thus she established that thorium is also radioactive. Notice that she used the method of difference to plan the experiment: she tested oxides of different metals and thus the experimental condition is the same except in the choice of metal.

After having identified uranium and thorium as the radioactive metals, Madam Curie asked: Is there any other radioactive element? She argued that in the minerals that contain uranium and thorium, the radioactivity due to these two elements individually should add up to give the radioactivity of the mineral. So she measured the quantities of uranium and thorium in these minerals, and checked if the radioactivity of the mineral is a simple sum of the radioactivity of the uranium and thorium present in the mineral. She found that this is true for most minerals, but in the mineral called pitchblende she found that its radioactivity exceeds that expected by considering its uranium and thorium contents individually.

Now she proceeded to apply the method of residues. She knew the intensity of radioactivity that can be produced by the amount of uranium and thorium present in a mineral. If the observed radioactivity is larger than the amount that can be accounted for from known sources, the residual radioactivity must be caused by a residual radioactive substance present in the mineral. So she hypothesised that pitchblende contains a hitherto unknown element that is highly radioactive. It was not detected in her chemical analysis because it occurs in minute quantities. This pursuit led to her discovery of two elements radium and polonium.

After the seminal contributions Hume, Kant, and Mill, many other scientists and philosophers of science tried to enrich the idea in various ways. But the groundwork laid by these philosophers has continued to this day, with rectification of the shortcomings of their ideas.

The most important additional understanding that has emerged is that there is *one* cause behind every event. Modern science does not accept the idea of plurality of causes. Plurality of causes is a common sense opinion which means that a given effect or phenomenon may have been the result of multiple or alternative causes. This is not a scientific viewpoint. Modern science says that for every effect there is a single cause.

Suppose a seed germinates into a plant. What was the cause? You would notice that the plant would not emerge unless the seed were there. Hence the seed can be said to be a cause. The seed would not have germinated unless water were there. Hence water is also a cause. That way one may make a common-sense statement that seed, water, soil, air, oxygen, appropriate temperature — all these are causes. But that would not be a scientific statement. A proper statement would be that all these put together creates a condition, which is the cause behind the germination.

If A and B together cause C, then A and B are not called causes individually; they are called 'factors' affecting the phenomenon. The cause in this case encompasses both A and B. The immediate antecedent of C, the collection of all the conditions occurring immediately before the occurrence of C will be called the cause of C. Galileo Galilei was the first to introduce this concept, but it went unnoticed for a long time. Scientists went on arguing on what constitutes cause of an event, while they were actually trying to identify the 'factors' included in the cause. For example, we now realise that the 'operational causality tests' proposed by Mill are actually the ways to locate the 'factors' included in the cause of a phenomenon.