Research Methodology
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Lecture - 24
What Scientists Actually Do, Part 02

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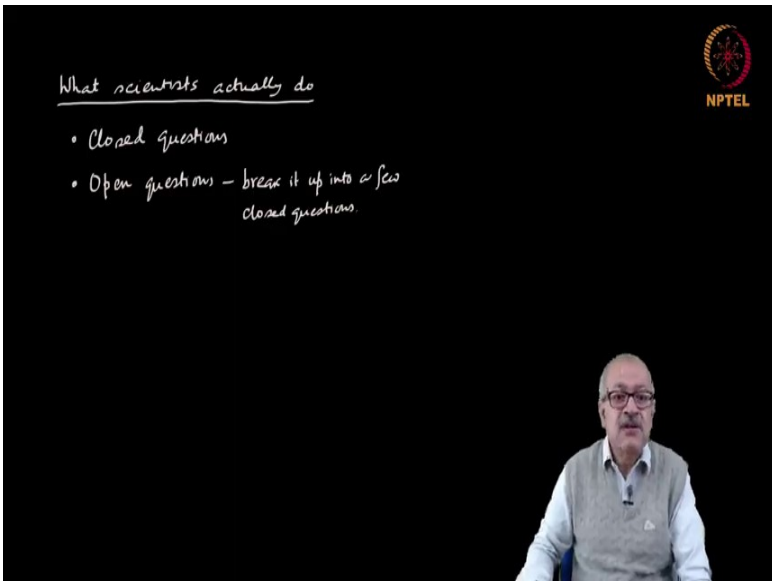

Now, once the question is well defined in one's mind, one has to proceed to obtain the answer to that question. There are a few steps a scientist takes and this is what I will enumerate now. The most important and the most prevalent method of answering a question is to formulate a hypothesis.

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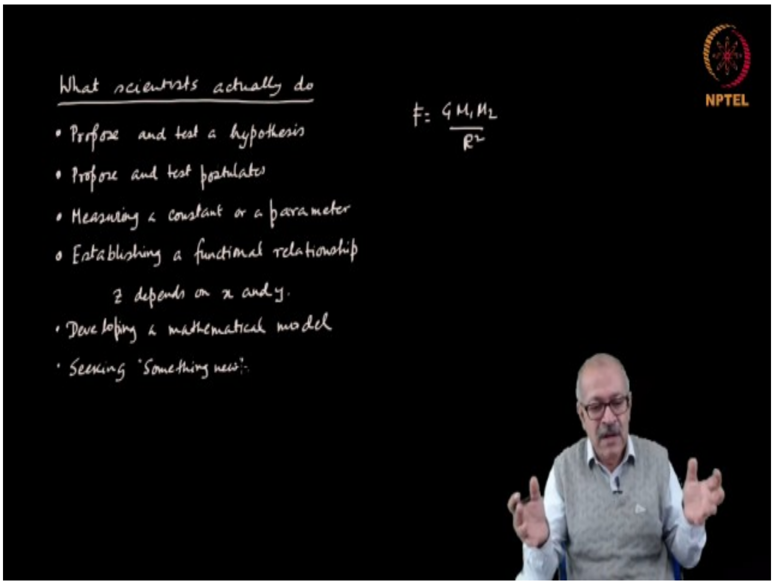

So, the first thing that one does is to propose and test a hypothesis. A hypothesis, essentially, is a scientific guess. The way to answer a ‘how did it happen?’ kind of question is to propose a hypothesis and test a hypothesis. This is almost the mainstay of science. Almost all science is built on proposing and testing hypotheses and therefore, I will spend separate lectures on that.

In today’s lecture, I am not focusing on proposing and testing hypothesis because more lectures will be needed for that. Effectively the point is that, if a question is there in the scientist’s mind, in order to answer the question the scientist guesses the answer and that guessed answer is the hypothesis. The hypothesis needs to be scientific and there are certain criteria for the hypothesis to be scientific. I will come to that later. Then one is to test the hypothesis.

Remember the time when I was dealing with philosophy and logic. I said that, if you start from a premise and use deductive logic, you arrive at something that is deductively obtained from this premise. If the premise is wrong, the deduction would be wrong, the result will be wrong. If the premise is right, the result will be right provided the deduction is correct, that means, it is a valid deduction. But if the premise is wrong, still a valid deduction can lead to a correct result. I have shown that. Right?

So, one can arrive at a true deduction starting from a wrong premise. Now, how do we test a hypothesis? Essentially, from the hypothesis that we make, we obtain, by applying deductive logic, certain experimentally testable predictions, and then you test it. So, when we have tested the hypothesis, actually we have tested some experimentally testable prediction from the hypothesis, which means that we have applied the logical structure that we have already done in this course.

Starting from a premise, apply logical structure, obtain a result. That result is what you are testing. If the result is tested experimentally to be false, then the starting premise is false. That provides a way of eliminating hypothesis. But otherwise, we cannot say that a test becoming correct directly means that the hypothesis was correct. So, one has to keep on testing further. I will come to come to details of this issue a little later.

The second thing a scientist does is to propose and test postulates or validate postulates. Postulates are also scientific guesses. But postulates are scientific guesses regarding a law of nature: this is something that always happens. While a hypothesis can be regarding a particular event: ‘how did it happen?’ kind of question, postulates are related to ‘how does it happen?’ kind of question, which means that these are related to laws of nature.

Let me give an example. When faced with the question: ‘how do all the planets move in particular ways (elliptical orbits with the central body at a focus) how does it happen?’ Newton guessed that it happens because any two bodies attract each other with a force equal to G M1, M2 by R square. It was a guess. But then he said that if this guess is true, if this assumption is true, then I can mathematically prove that the orbits of planets should be the way they are.

So, when a scientist proposes a postulate, what is his statement? The statement is that I am making a guess. I am a making an assumption. But if I make that assumption, then I can show that that is true which is actually observed.

So, in making a postulate, the scientist takes a shot at some law of nature. A law of nature means something that is universally applicable, not to any particular body, what is universally applicable. And he says that, ‘if I assume that, then I can show that should happen’.

At one time, it was a quandary why the atoms are stable. The electrons, by the law of electromagnetism, are supposed to spiral into the nucleus and supposed to fall into the nucleus. But they are not falling. The things around us are stable. How does that happen?

Niels Bohr made the postulate that electrons can occupy only specific levels, specific orbits; and only when an electron makes a transition from one orbit to another, either it absorbs a specific amount of energy or it releases a specific amount of energy. So, that was his postulate. If I express his point correctly, he would say, ‘I do not know why this is true. But, if I assume that, then I can show why what is observed is observed’. That is the character of a postulate.

When people could not explain various phenomena in the micro world, most important being the black body radiation curve that I talked about in a one of the earlier classes, then the idea of quantum mechanics developed. The problems concerned the stability of atoms. The problems concerned why do particular orbits are there the way Bohr postulated? You can try to obtain another postulate whose consequence will be a postulate that was proposed earlier. In fact, that is what happened in quantum mechanics.

So, those who developed quantum mechanics between 1925 and 1927—a short span of time, but practically the whole edifice of quantum mechanics was developed in this period—they said that, let us assume that the state of any particle is completely given by a complex number psi. It was a postulate.

The scientist would say, I do not know why that happens. I do not know why it is true. But if I assume that, then I can show this. Then they said that, whatever are the observables, what we can observe, like a particle’s position, momentum, energy and things like that—those are represented by operators, mathematical operators. It is a postulate. The scientist would say, I do not know why this happens, but if I assume that, I can show this.

Then they said that, what we can actually observe in an experiment are the eigenvalues of these operators. A postulate. There is no reason to believe why it should be so, but they said that, if I assume that postulate, then I can show why the nature behaves the way it does. So, that is the character of postulates. In postulates we are taking a shot, a guess, at a law of nature.

But these postulates have no explanation by themselves. These are assumptions. But the scientist says, ‘if I make that assumption, then I can explain why this happens’. That is the character of a postulate.

So, a scientist’s main activities are proposing and testing hypotheses and proposing and testing postulates.

The third one: measuring a constant or a parameter. Measurement. And most of the tests of hypotheses and postulates involve measurements.

So, measurement is a very important activity in science. I will deliver a separate set of lectures on the issues involved in measurement. In measurement, essentially you need to have something that is measurable in the first place, something which can be ultimately converted into a number, and that number has to be measured. That number then is used as a test of a hypothesis or a postulate or to understand something in nature.

How far is the Earth from the sun? It was a major measurement problem for a long time. A major measurement problem because there is no direct way to measure it. It cannot be measured by parallax. I have already told you what parallax is, but the distance between the Earth and the sun cannot be measured that way because the stars behind the sun cannot be seen and therefore, the parallax cannot be measured. So, that constituted a problem for a long time.

So, measurement is a very important activity in science. Once you have done a measurement, then we try to construct theories out of it. The way to construct theories, for example, I have a question regardings a phenomenon where there are certain variables and I do not know how this variable affects that variable and so and so forth. So, I perform an experiment and that indicates that there is a functional relationship between the two variables. That prompts us to develop a theory.

So, measurement often leads to certain functional relationships between variables. That is another important activity that we do: establishing a functional relationship. The functional relationship is always between an independent variable and a dependent variable.

So, whenever we are investigating a phenomenon, within that we try to identify what is an independent variable, which can be independently varied. That means, the experimenter has the ability to vary that independently of other things. Other parameters vary as dependent on that, so these are the dependent variables or parameters.

Often it is found that there is a dependent variable and an independent variable, but the dependent variable is dependent not only on one variable, but many. Suppose z depends on x and y. Then, in order to obtain the functional dependence, we have to keep y constant, first vary x and see the variation in z. Then keep x constant and vary y, and observe the variation is z. Then, combining these informations, we can find out how z depends on these variables. But we can definitely state that, if y is constant then z depends on x in a particular way.

The Boyle's law, Charles' law, etc., are established exactly that way: one thing is kept constant, the other thing varies. The way to obtain these functional dependences involve plotting graphs, getting a best fit graph. One has to get a best fit plot because the points will be scattered, they will have errors. One has to get a best fit curve and then fit that curve to some kind of a functional form.

How to do that? We will come to that again in a later lecture: how to obtain the functional dependence. For example, it is easier to find a linear functional relationship. It is relatively more difficult to obtain a non-linear functional relationship because various non-linear functions would tend to satisfy a particular variation.

Normally, either we try to obtain a linear relationship or a power law relationship which can be obtained by drawing a log plot. We will come to that later. So, establishing a function relation.

Once we have established a functional relationship, then that prompts theoretical thinking. One can think why is this functional relationship true. This is exactly what happened in case of the black body radiation. People asked why is this true.

Or one can have a prior theoretical basis, which told us that a function relationship should be linear. During the experiment you can fit a linear function and find out the slope of that line, thereby extracting a parameter, which again is fed into the theoretical work. So, the theory and experiment actually go hand by hand.

After one goes through this process of establishing a functional relationship, one has to develop a mathematical model. Developing a mathematical model of physical phenomena. ‘Physical’ means not only concerning physics. In all fields of science, even social science, developing a mathematical model is a very fruitful important activity because that enables prediction. If you have a mathematical model, not only just a causal relationship stated as a sentence, but also a mathematical functional relationship, then if something happens, what is going to happen that can be predicted and that can be tested.

So, the way to go forward in science is therefore, to develop mathematical models of the things that we see around us. And mathematical models, even mathematical models of biological systems, often lead to certain insights into the biological phenomena. Not only insights, but opens ways of investigation into biological phenomena which would be impossible if the mathematical model were not build. And so, building a mathematical model is a very important scientific activity that we engage in all the time.

Finally, this is somewhat rare, but still we are seeking something new. Well, that is what the scientists does all the time. But in the early days, people were all the time seeking something new. But now most of the things are explored. And therefore, we can seek something new only when we develop a new apparatus, a new way of doing something that was not possible before.

For example, when Galileo first invented the telescope, he looked at the sky without any premonition about what he is going to see. He saw new things. He was looking for something new and he see saw things that were new: he saw the satellites of Jupiter, phases of Venus and so and so forth.

When the 200 inch Mount Wilson observatory with a large telescope was built, Edwin Hubble looked at the distant galaxies, looking for something new. And he found something new. When people first developed the way of cooling something to very close to absolute zero, then people started wondering what can you see at this temperature. Something new. This ‘something new’ can be explored only if you develop a technique, develop an apparatus, to do something that was not possible before.

And today the particle physicists are building bigger and bigger particle colliders, stronger and stronger, with larger energy. Why? Because, by colliding particles they are seeing what is new. They are trying to see what is new.

So, seeking ‘something new’ is still possible, but consequent to your developing something, some ability, some way of exploring the material world in a new way, then only it is possible.