Chapter 2

What Scientists Actually Do

Scientists ask questions regarding some aspect of nature or society, and seek answer to the question. There are various methods of seeking answers, which we shall discuss in this chapter. But the most important aspect of all scientific research is to form scientific questions.

2.1 Forming scientific questions

What is the difference between a scientific question and an unscientific one? Basically the difference lies in three aspects.

1. Scientists always ask questions that can be answered following well-defined procedures. Questions that are too vague or too general do not form basis for scientific investigation. Some examples of such 'too vague' or 'too general' questions are "What is the meaning of life?", "How did everything come into being?", etc.

2. Scientists always frame the questions based on the knowledge that is already existing. We learn what is already known on a specific subject by reading books, journals, and other source-material. Then, based on that knowledge, we ask further questions. Uninformed questions are not considered scientific.

3. Scientists ask questions regarding material processes and phenomena, while a person untrained in scientific method may also harbour questions based on personal beliefs in supernatural entities like ghosts, soul, magical powers of planets and stones, etc. Such questions do not form basis of scientific investigation.

Some scientific questions are of “How did it happen?” type. Examples of such questions are

- How did the Himalayas form?
- How did the moon come into being?
- How did the Indus Valley civilization end?
- How did life originate on Earth?
- How did the great Bengal famine of 1943 happen?

Some scientific questions seek the value of a parameter or a constant, like the value of the gravitational constant, the mass of the tau-neutrino, the specific gravity of molybdenum, etc.

Some questions are of the ‘why’ type, seeking the reason behind something:

- Why is a leaf green?
- Why is the sky blue?
- Why do we see only one side of the moon?
- Why does sugar dissolve in water but sand does not?

Thus, all scientific questions start with ‘How’, ‘Why’ ‘What’ or some such word, address some aspect of a material process or phenomenon, and end with a question mark ‘?’. All scientific investigations start with such questions.

Some questions are of the type that, if you find out the answer, the question is closed, i.e., it does not lead to further questions. Such questions are called ‘closed questions’. Some examples are:

- What is the specific gravity of water?
- What is the derivative of $\tan\theta$ with respect to θ?
- How many eyes are there in the compound eyes of a dragonfly?

Closed questions can be answered by following well-defined procedures. If the answer is already known, one can simply look it up in literature.

Some questions are called "open questions" — the ones that are relatively harder to answer, and obtaining the answer does not close the matter; it leads to further, more refined, questions. Some examples are:

- How does the stock market collapse in one country lead to economic problems in another?
- Why is the sky blue?
- How does the genetic information lead to the development of the body parts of an organism?
- Is there really a "dark matter" that is invisible but can exert gravitational influences?

Scientists mostly have such open questions in mind when they conduct research. The way to address an open question is to break it up into a number of closed questions. If one obtains the answers to the closed questions, then the open question, or at least some aspect of it, can be answered. In some cases the smaller question may not be a 'closed' question as defined above, but at least it should be a 'testable' question, where specific activities enable one to obtain an answer.

At any point of time a scientist really is seeking answer to one of the closed or testable questions. But behind it the "big picture" is formed by the open questions he or she has in mind.

2.2 Proposing and testing hypotheses

Faced with a scientific question, scientists form intelligent guesses, called hypotheses. These are scientifically formulated guesses about the possible answer to the question. In answering a scientific question, proposing hypotheses is often the main line of attack. That is why, proposing and testing hypotheses are often considered to be *the* method of science. This will demand much detailed exposition, which will be taken up in Chapters 3 and 7.

2.3 Proposing postulates

Postulates are scientific guesses at how nature works. All postulates are proposed to explain something observed in nature. In proposing a postulate, a scientist would say, “If we *assume* such and such to be a law of nature, I can explain the observations.”

A typical example is Newton’s proposition regarding the law of gravitation. The observational basis that provided the ‘clues’ were the motion of projectiles observed on Earth, the observed motions of the moon and the planets, etc. To explain these, Newton’s approach was “if we *assume* that two bodies attract each other with a force proportional to the product of the masses and inversely proportional to the square of the distance between them, then I can explain the observed motions.”

In trying to explain absorption and emission of radiation by matter, Niels Bohr guessed that electrons in an atom can occupy only a few discrete energy levels and can jump between these, thus absorbing or emitting discrete ‘packets’ of energy. This postulate succeeded in explaining a lot of things observed in nature, even though Bohr did not know at the time of proposing the postulate *why* it should be so.

Quantum mechanics rests on a few postulates, like “the state of a particle is completely specified by a complex number Ψ,” “observables are given by operators”, “every measurement of an observable yields one of the eigenvalues of the corresponding operator," etc. We do not know why these statements are true. But if we *assume* these, we can explain a lot of physical phenomena and can predict many more—the outcomes of specific experiments.

Thus, faced the task of explaining some observation, a scientist would guess an underlying law of nature, and the line of argument would be "if I assume this, I can explain that." Notice that a postulate is useless unless it helps in explaining more than what it was initially intended to explain. A postulate must have predictive power, which forms the basis of its test. The experimental outcomes predicted by the postulate are checked by actually performing the experiments. If the result of an experiment does not match the prediction, the postulate is rejected. Otherwise it is provisionally held to be true and further, more refined, experiments are devised to test it.

While proposing a postulate, a scientist has to satisfy a few conditions. These are the same as those for a hypothesis. These are presented in Chapter 3.

2.4 Measuring the value of a parameter or a constant

Many of the closed questions involve measuring a value, like the value of the universal gravitational constant G, or the mass of an electron. One may also need to obtain some measurable characteristics like x-ray diffraction pattern or NMR spectrum. Some measurements may involve relatively simple experimental procedure (like measurement of a resistance) or may require a very elaborate experimental apparatus, often with involvement of hundreds of scientists (as in most particle physics experiments).

The demands of each experimental situation is particular. The common features involve estimation of experimental errors, which will be taken up in detail in Chapter 4.

2.5 Establishing a functional relationship

Most often a hypothesis involves some relationship between an independent variable and a dependent variable, which the scientist has to establish through an experiment.

The first step in planning such an experiment is to identify the independent and dependent variables. Let us call the independent variable as x and the dependent variable as y. Often you would find that some other variables might also affect the dependent variable. If you really want to find the functional relationship between x and y, then you have to figure out how these 'other' variables can be kept constant while performing the experiment. Then you have to plan ways to vary the independent variable in steps and to record the values of y in every step.

After the experiment is performed, one has to plot the values of y against the values of x. The visual appearance of the graph is often indicative of a functional relationship. One has to guess the function (sometimes the form is suggested by theory) and then one has to obtain the unknown parameters appearing in the function (for example, the values of A and B in the linear function $y = A + Bx$) by least square fitting. A power law dependence ($y = a\,x^{\gamma}$) is better visible in a logarithmic plot.

2.6 Developing a mathematical model

Some research involve development of a mathematical model of a physical system. If the causal connection between the different processes occurring within that system are known as mathematical relationships between variables, the model of the process can be formed out of that knowledge. If the causal connections are not known in mathematical details, then phenomenological models can be constructed. One can also guess certain mathematical forms from experimental observations and then can test these by further experiments.

Since mathematical models are an integral part of modern science, we include a detailed discussion on it Chapter 8.

2.7 Seeking 'something new' by observation or experiment

When a scientist has developed a new experimental or observational technique, he may look for something new that the new technique may reveal. In such a case the scientist may not have any prior idea about what may be found. For example, when Leeuwenhoek first developed microscopes, he observed microscopic organisms that were not known before. When the 100-inch Mount Wilson observatory was constructed, Edwin Hubble managed to identify individual stars in distant galaxies. When a new technique to cool a substance to ever lower temperatures is developed, scientists try to find what new properties of substances (for example, the property of super-fluidity in liquid helium) manifest under such conditions.

However, in modern science experiments with the mood of "let us see what happens" are seldom pursued. Almost all experiments are conducted to test some expected outcome, as predicted by a hypothesis or a postulate.

2.8 Putting it together

We have discussed above the different techniques a scientist may adopt to conduct his/her research. But at the base the scientist has an open question in mind and the methods he or she adopts enables him or her to find the answers to the closed questions. But ultimately the scientist has to put it all together to figure out an answer to the open question.

Sometimes a PhD work may involve finding the answer to a closed question that the supervisor gives the student. Often it is found that the student has no idea of the 'big picture' from which the question came. Such situations lead to improper training of the student. The student must know the bigger open question that his or her research might help answering. Sometimes students are found to be so bogged down by the tools and techniques of conducting the investigation, the conceptual aspects evade their attention. This is to be avoided consciously.

Most scientific work actually are small incremental steps in unraveling the mysteries of nature. Work of momentous impact like that of Newton, Darwin, or Einstein are few and far between. Most science is pedestrian science, where a scientist painstakingly works out something that was not known before. The person who first measured the perihelion shift of Mercury is not very well known. But that observation sowed the seed of suspicion about universal applicability of Newton's theory of gravity, which led Einstein to develop his General Theory of Relativity. The person who first measured the character of blackbody radiation is not very famous. But his observation was at the base of a complete paradigm shift in physics that occurred with the development of quantum mechanics. Science proceeds with such small steps, and each one is important—so long as these are obtained following correct scientific procedures and are reported in a proper form so that other scientists come to know about it.