Aspects of Quality Learning in Science

Introduction

The new Vigyan Pratibha (VP) project aims to facilitate high quality learning of science and mathematics by school students at the secondary stage (Classes 8, 9 and 10) by encouraging their deeper engagement with science and mathematics than is possible in traditional classroom and laboratory teaching.

In this article, we attempt to identify and elaborate on the different aspects of what might be regarded as 'quality learning of science'.

The twelve key aspects/dimensions of quality learning in science suggested below derive from current perspectives of science education the world over as well as HBCSE's grassroots experience in science education over many years. These different aspects are not strictly independent; they overlap considerably and ideally should reinforce one another. Importantly, they are conceived to apply to all stages (elementary, secondary, and higher stages) of education. They are also common to all different subjects of science: physics, chemistry, biology, astronomy, geology, environment, etc.

Thus the aspects of science learning that we discuss here are very general; it is the expected learning outcomes or competencies that have to be stage specific and age appropriate, and need to be spelt out separately for each different subject of science. An accompanying document will detail out these expected competencies at the secondary school stage of science learning. The list of specific expected competencies covering all the general aspects in different subjects of science for a particular stage is often termed the 'science standards' for that stage.

We must add that there is nothing sacrosanct about the number (12) of different aspects of science learning and their characterization given here. Different people may have different views and perspectives on how best to classify them and could come up with different combinations of the aspects listed here. However, we believe that, in the aggregate, there is a fairly broad global consensus about what all aspects are necessary for high quality science learning, in whatever ways we may put them. There may, however, be considerable divergence in views regarding the pedagogical approaches to implement the consensus. Apart from occasional observations, this article does not dwell in detail on pedagogic issues. Appropriate pedagogic strategies should evolve through actual experience of teachers and other stakeholders as the project gets going. See, however, some remarks at the end.

Twelve Aspects of Science Learning

1) Knowledge of scientific facts, principles, and laws

Science has a large body of empirical and theoretical knowledge that includes numerous observed regularities and patterns in nature, and principles and theories to understand them. Though science is always tentative and subject to revision, much of the present core of scientific knowledge is robust and likely to survive, at least in some sense, as an approximation to the more advanced science in the future. Students need to be familiar with this well-established knowledge as appropriate to age/stage of learning.

Traditional science curriculum does include this aspect, and indeed this must be a central aspect of any science curriculum. We can only add that the knowledge component of the traditional curriculum does not give adequate emphasis on numbers and order of magnitude-estimates of the quantities involved in different contexts in science. Concepts and scales of quantities are intimately related in science, a point rarely stressed in school science education.

2) Proficiency in basic process skills of science

Learning science involves several general process skills: careful observation, classification and systematization of data, looking for regularities in data, inferring significant patterns as well as noting anomalies or deviations from them, displaying data graphically, etc. Basic mathematical, numerical and statistics-based skills, and facility in drawing schematic figures and diagrams may also be regarded as part of the 'skills set', as is proficient use of common workshop tools and standard electrical/electronic instruments. In the new internet age, the basic 'skills set' is now enlarged to include efficient use of computers and internet resources. The knowledge versus process approach has long been a matter of debate in science education. We adopt a middle position: some process skills are domain specific, while some like those mentioned above are general and transferable across different domains of science and students must develop adequate proficiency in them.

3) Conceptual and procedural knowledge of experiments in science

Experiments have a central epistemological role in science, distinct from that played by observations of nature, however detailed. They allow us to control variables in a phenomenon selected for study, and hence are better suited to support/reject theories or suggest new theories. Good scientific theories give unambiguous predictions that can be tested by experiment. Thus ability to carry out a given experiment properly is basic to learning science.

The experimental ability goes much further than just knowledge of facts and laws, and proficiency in process skills already covered under the first two heads—hence a separate head for this aspect. It is certainly partly domain specific. The experimenter needs to have good familiarity with the subject and its concepts, especially those that bear on the proposed experiment. But conceptual knowledge is not enough. The experimenter needs to have a feel for what physical quantities will more readily admit of measurement in a given context, and what measurement methods will be more suitable for greater precision, given the available (or proposed new) tools in the laboratory. S/he needs to plan the procedure in detail, the range of variables to be measured, the variables to be controlled, the possible sources of error and the ways to reduce them. A thorough error analysis is basic to a good experiment, both before and after carrying it out. All this is part of the procedural knowledge of the experiment.

This aspect is sorely neglected in school education in India. Experiments (or 'practicals'), if they are done at all, are carried out as set recipes to verify some prior knowledge, i.e., to obtain some standard result. The immense learning potential of the activity of experiments is barely realized.

4) Proficiency in solving given problems (with known solutions to mentors)

This aspect refers to applying and adapting the knowledge learnt in classroom and laboratory to problems that have unambiguous solutions that are known to the teachers/mentors. It is based on the common wisdom that general or abstract knowledge is better internalized through practice with numerous exercises and problems in context. Though problem-solving activity of this kind is generally held in theory classes, practice problems can be given in a laboratory also.

The traditional approach to science teaching does recognize this aspect as important to science learning. However, in practice, this mostly reduces to doing some 'plug-in exercises' or at most a few standard types of problems. Students are rarely exposed to challenging problems or problems involving rich and varied contexts. Problem-solving activity has much potential for bringing in other vital aspects of science learning, such as collaborative learning, and critical and coherent understanding of science. (See below.)

5) Ability in modeling: mathematical, physical, computer-based models of structures, functions and processes.

Modeling is central to expert practice in science. Models are approximate representations of reality. However, representation of a given phenomenon is not unique; it depends on what features of the phenomenon we wish to focus on. A model can be a concrete physical model, a schematic model simulated on a computer or a mathematical model, analytical or computer-based, or a combination of these types. Scientists attempt to understand, reason and explore the world through models. Students need to practice the same at age/stage appropriate levels of the subject. Modeling promotes active learning of science. The availability of computers on the one hand, and the increasingly recognized importance of visuo-spatial dimension in cognition of science on the other have made the activity of modeling an important new tool of learning science.

6) Critical understanding of science and appreciating its coherence

A curriculum that incorporates the different aspects of science discussed above naturally facilitates a critical appreciation of science at the required stage. Yet, there is merit in stressing this aspect explicitly—hence a separate head. Despite its empirical basis, science is a formal, technical knowledge system built on a whole range of basic concepts many of which go against our intuition. Thus it is not surprising that there are numerous domain specific conceptual pitfalls in learning science. Critical learning involves being alert to these pitfalls and developing the ability for clear conceptual discrimination.

Criticality ties up with appreciating another key feature of science: its extra-ordinary coherence. Science is a complex web of interconnected concepts and facts. The different disciplines of science (and the sub-disciplines within a discipline) have varying degrees of autonomy, yet they all cohere with one another. To put it somewhat simplistically, biology does not need a separate chemistry of its own, and the principles of chemistry do not contradict the basic theories of physics. (This does not necessarily imply reductionism, but it does signify internal consistency in the edifice of science as a whole.) It is this coherence that makes interdisciplinary areas possible, and in fact, currently, they form some of the most exciting frontiers of science. Critical learning of science emphasizes the linkages between different concepts and facts and how they are positioned in the subject as a whole. It entails proper appraisal of claims and their justification in a scientific argument, careful look at the assumptions and approximations (both tacit and explicit) in scientific explanations, and also critical evaluation of competing ideas and theories.

7) Understanding 'Nature of Science'

Understanding 'Nature of Science' is now regarded an integral part of learning science, no less important than understanding its content. This aspect involves examining the methods of creating and justifying scientific knowledge. It includes looking at the cognitive and communication practices of experts, the role of scientific institutions and societies, and the ethical and social norms of the scientific community. A rather simplistic description of the 'Scientific Method' appears in introductory chapters of most textbooks of science. However, we have now come to appreciate that the practices and norms of science and the dynamics of its knowledge generation activity are for more complex. This has been a subject of continuing scholarly debate, particularly over the last century. Despite the widely differing perspectives, a broad consensus about some key aspects of 'Nature of Science' has emerged nevertheless. Most science educators advocate the view that this broad consensus should be communicated in age appropriate ways at every stage of learning science.

Learning and teaching 'Nature of Science' may seem daunting, even unsuitable, for school science education. It would indeed be so if it was condensed into some abstract generalities to be learnt separately from the rest of science. Nature of science can be best learnt in context, by interleaving it with the content of science. History of science is the most natural setting to appreciate 'Nature of Science' as we learn how the modern concepts and laws of science evolved from their historical beginnings. Another promising approach to learn 'Nature of Science' uses the 'Inquiry' methods currently being favoured. See below.

8) Inquiry and creativity in science

This aspect subsumes nearly all aspects of learning science discussed so far, but it goes much beyond them in that it stresses on learning the inquiry process adopted by scientists in their professional work. It basically proposes that to learn science, you should do what the scientists do; ask a meaningful question and pursue a systematic investigation to arrive at an evidence-based answer or explanation. For carrying out the investigation, you will obviously need some prior scientific knowledge and other resources. This requirement can be either met independently, or, more realistically, with the help of a teacher/mentor. Depending on the extent of the teacher's intervention, Inquiry may be self-directed or guided with varying degrees of the two modes in a particular inquiry task. Inquiry may have predetermined goals (set by the teacher) or may be completely open-ended. Learning to carry out open-ended inquiry can in time foster creative ability in science among students.

Inquiry may be regarded as a higher order process skill of science that, unlike the process skills mentioned under (2), is not content independent. Learning here is woven around the domain of inquiry and needs other aspects of science such as knowledge of scientific facts and laws, problem solving, observations, experimentation, critical thinking, etc., discussed under different heads above. The pedagogy that centres on this aspect is now widely advocated and is called the Inquiry-Based Learning (IBL) approach to science.

9) Design and Engineering skills and innovation

We are often made aware of the two distinct cultures of humankind, the scientific culture and the culture of arts and humanities. It is less often realized that the rapid advances in science in the last century and the accompanying technological progress have given rise to a distinct new culture, that of 'design and technology'. This large scale human activity applies the principles of science in designing and implementing new technological solutions to the needs and problems of our societies. Clearly, while science is universal, technology and design pertain to the local context. That is, a technological design suitable for one context may be unsuitable for another and replaced by an alternative design, though both may be based on the same scientific principles. Innovation is a key feature of a technological solution (hence the numerous patents for different solutions of the same or similar problem), which is also profoundly guided by considerations of aesthetics and economics and even by the local cultural values of the society.

Unfortunately, this new culture of design and technology is nowhere to be found in our science curriculum. It is true that experimental work in science needs considerable familiarity with instruments and tools and other technological products. But that hardly amounts to enculturation in design and technology as an autonomous intellectual activity—this is why we have not subsumed it under the head related to experiments (3), but assigned it a separate head. Many science educators now believe that just as familiarity with basic mathematics is necessary for learning science, basic design and engineering skills (resulting in innovative and aesthetic technological products) must be integral to learning science at all stages. This new perspective of science education has resulted in science curricula of several countries incorporating design and engineering skills in age/stage appropriate ways. It is time that we in India also took steps to incorporate this aspect in our science curriculum.

10) Awareness of socio-scientific issues

For human societies, Science and Technology is a mixed blessing. Its impact on human welfare can be both benign and harmful. The development of electrical and electronic technology and their use in almost every tool, instrument and gadget of daily use, the enormous progress in transport and communication, the eradication of many deadly diseases that killed millions in the past and the rise in human longevity may be cited as some among many benign consequences of scientific progress. The rapid strides in computer-based technology in the last three decades ushering in the digital age are another example of how science and technology directly affect our ways of living. On the other hand, uncritical and unwise use of technology for short-term gains has thrown up serious issues of environmental destruction, pollution and new health hazards, etc, while technologies of warfare have caused destruction on a scale inconceivable in the past, and, if unchecked, pose alarming prospects of mass destruction on a global scale.

In short, Science and Technology have now permeated every aspect of human life, and numerous complex issues—socio-scientific issues—have arisen as a result, whose resolution is beyond the scope of science and lies in the realm of ethics and values of a society, and, therefore, need sociopolitical intervention. Good science education would require students to be aware of these socio-scientific issues and enable them to develop their own informed and mature views about them.

This dimension of science learning is vital, but must be incorporated in our curriculum with care, sensitivity and balance. The age of the student and the stage of learning must always be kept in mind. Over-all it should lead to a positive image of science and optimism about its benign role for human welfare, even as students are made keenly aware that proper ethical and moral choices at individual and social levels are essential to materialize this role.

11) Collaborative learning of science

Collaborative learning of science has both cognitive and affective gains. Several science education studies have shown that this mode of learning science is effective, particularly for complex and context-rich problem-solving in theory and experiment. Generally, the group's work is found to be better than what its ablest member would do individually. Moreover, collaborative learning can address the problems of class and gender inequities in the school system and reduce the gap between the underperforming and meritorious students. Thus an important aspect of learning science is to cultivate attitudes of co-operation, responsibility and friendly intellectual interaction with peers necessary for collaborative learning to succeed.

This is, no doubt, partly an affective dimension to science learning, but one that has become very relevant in modern times. With the increasing complexity and diversity of theoretical and experimental requirements of current scientific research, it is no longer realistic to carry out research all by oneself (excepting some individuals and areas of work), and collaborative science has now become more a norm than an exception. A science curriculum that recognizes the importance of co-operative learning at school not only improves students' learning outcomes and helps bridge their divides, but also prepares them for collaborative scientific research, should they opt for science careers in the future.

12) Ability to communicate science to peers and others

Science is a now a social enterprise on a global scale. Scientists across the world need to constantly interact with one another through oral and written communication, besides frequently having to describe their work to other members of public: the end users of science, policy makers, and so on. Clearly, one important aspect of learning science is to develop the ability to communicate scientific ideas properly to our peers as well as to others. The new media tools have greatly enhanced the power, precision and speed of scientific communication, and familiarity with them is now part of learning to communicate science.

Language is basic to any communication. Scientists, of course, use some natural language to express their ideas, but the language of science is quite distinctive. The distinction is evident when mathematics and other signs and symbols, diagrams graphs, numerical tables, etc. are part of the communication. However, even without these non-verbal modes, scientific language has a different flavor and style from the way lay people use a natural language. There are unstated conventions of oral and written modes shared by the scientific community. Learning a scientific discipline amounts, in part, to acquiring the expert language of that discipline.

There are deep issues surrounding language and cognition. Language is not only a passive tool to express our ideas; it shapes them constrained by its syntax, semantics and pragmatics. The implication, though debatable, is that users of different languages may have subtly differing cognitive representations and understanding of common scientific concepts. These matters get further complicated in a multilingual society such as ours with science often learnt in a non-native language (English). Despite these difficult issues, there is little doubt that as part of science learning, students must develop competence, in whatever language they prefer, in articulating their ideas with the clarity and precision required for scientific communication.

Concluding Remarks

We have attempted to list out and clarify the different aspects that should inform any science curriculum that focuses on quality learning of science in its broad sense. We reiterate that these aspects pertain to all stages, from the elementary to the higher stages of science education. The general and somewhat abstract description of each aspect in this article could lead to the erroneous impression that some aspects pertain only to the more advanced stages of learning. The general aspects should become clearer in the document on 'science standards for the secondary stage', where the competency levels expected at that stage are detailed, reflecting the general aspects discussed here in more concrete and discipline-specific terms.

As remarked earlier, we have not discussed here the crucial matter of what pedagogy to adopt for implementing these aspects and enabling pupils to attain the required science standards. However, whatever pedagogic approaches we might go for, they should certainly emphasize active and participatory learning of science, and depart radically from mere drill and rote memorization. Most importantly, any pedagogy that we use must be sensitive to the issues of class, gender, rural-urban divide, etc., and promote equity and access for all students. Special pedagogies will be necessary to ensure access for the physically challenged pupils. But the aspects of quality learning of science described here are universal and remain the same for every pupil.

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