PRINCIPLES-BASED ADAPTIVE TEACHING

ROUTLEDGE

Science Education

Developing Pedagogical Content Knowledge

Shamin Padalkar, Mythili Ramchand, Rafikh Shaikh and Indira Vijaysimha

SCIENCE EDUCATION

The book presents key perspectives on teaching and learning science in India. It offers adaptive expertise to teachers and educators through a pedagogic content knowledge (PCK) approach. Using cases and episodes from Indian science classrooms to contextualise ideas and practices, the volume discusses the nature of science and aspects of assessments and evaluations for both process skills and conceptual understanding of the subject. It examines the significance of science education at school level and focuses on meaningful learning and the development of scientific and technological aptitude. The chapters deal with topics from physics, chemistry and biology at the middle- and secondary-school levels, and are designed to equip student-teachers with theoretical and practical knowledge about science, science learning and the abilities to teach these topics along with teaching.

The book draws extensively from research on science education and teacher education and shifts away from knowledge transmission to the active process of constructivist teaching-learning practices. The authors use illustrative examples to highlight flexible planning for inclusive classrooms. Based on studies on cognitive and developmental psychology, pedagogical content knowledge of science, socio-cultural approaches to learning science, and the history and philosophy of science, the book promotes an understanding of science characterised by empirical criteria, logical arguments and sceptical reviews.

With its accessible style, examples, exercises and additional references, it will be useful for students and teachers of science, science educators, BEd and MEd programmes for education, secondary and higher secondary school teachers, curriculum designers and developers of science. It will interest research institutes, non-governmental organisations, professionals and public and private sector bodies involved in science outreach, science education and teaching and learning practices.

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Routledge
Taylor & Francis Group
LONDON AND NEW YORK

Cover image: Karen Haydock, Teachers scaffolding science learning through multiple modalities

First published 2023
by Routledge
4 Park Square, Milton Park, Abingdon, Oxon OX14 4RN

and by Routledge
605 Third Avenue, New York, NY 10158

Routledge is an imprint of the Taylor & Francis Group, an informa business

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record has been requested for this book

ISBN: 978-0-367-48592-4 (hbk)
ISBN: 978-0-367-49823-8 (pbk)
ISBN: 978-1-003-04750-6 (ebk)
ISBN: 978-1-032-27255-9 (ebk+)

DOI: 10.4324/9781003047506

Typeset in Bembo
by Deanta Global Publishing Services, Chennai, India

To Dr Narendra Dabholkar
A person who lived and died for making scientific temper part of our lives.

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SERIES EDITORS' NOTE

The last two decades have seen developments of national importance in school education in India. With the Right of Children to Free and Compulsory Education (RtE Act, 2009) and the National Curriculum Framework (NCF, 2005), changes have been afoot to enable access to quality education for children at scale. Responding to the concurrent need for teacher education to support the vision of a robust education system, the National Curriculum Framework for Teacher Education (NCFTE, 2009) recommended substantive changes in curriculum and practice of teacher education in the country. Subsequently, the high-powered committee on teacher education set up by the Hon. Supreme Court of India (Justice Verma Committee, 2012) endorsed these curricular reforms and called for an overhaul of the sector. Notably, similar shifts have been observed across the world, as teacher education programmes discuss pathways for professional development to enable teachers to work as transformative professionals in the 21st century. UNESCO's Sustainable Development Goals (SDG) call for transformative pedagogies, with a shift towards active, self-directed participatory and collaborative learning, problem orientation, inter- and trans-disciplinarity and linking formal and informal learning (UNESCO, 2017: 7). Acknowledging the need for gearing up the Indian education system to meet SDGs, particularly SDG 4 to ensure inclusive and equitable quality education and promote lifelong learning opportunities for all, the recent National Education Policy (2020) has proposed re-envisioning teacher education in multi-disciplinary institutions that can prepare teachers to meet the needs of learners in the 21st century.

With rapid advancements in science and technology, and the pervasiveness of ICT and media in our lives, the education sector stands witness to radical changes that are affecting teaching-learning practices in schools. Arguably, the onset of the Fourth Industrial Revolution requires preparing learners for a range of competences including effective communication, intercultural sensitivity, analytical and critical thinking, problem-solving skills and creativity, which extend beyond content knowledge. In this context, educators are required to gain adaptive expertise to prepare themselves and their students for uncertain futures.

A dearth of good curricular resources has been consistently identified as a key lacuna, from the first national commission on education in independent India, in preparing teachers as professional educators. In the light of the present education policy calling for substantial changes to teacher education, there is an urgent need for quality teaching-learning materials that can trigger critical inquiry, invoke a sense of adventure and provoke the curiosity of both student-teachers and teacher-educators to embark on the complex task of learning to teach.

To this end, the Centre of Excellence in Teacher Education (formerly, the Centre for Education, Innovation and Action Research, or CEIAR) at the Tata Institute of Social Sciences, Mumbai, has developed a series of textbooks under the theme 'Principles-Based Adaptive Teaching' that make inroads into the content and pedagogical domains of study relevant to teaching-learning practice. The titles for these books have been identified based on a consideration of the NCFTE 2009, emerging understandings from comparative studies of teacher education curriculum in the international context and demands from the field to address the needs of preparing teachers for the 21st century. Drawing from current research in education, the textbooks adopt an innovative, practice-based approach to transact the selected topics. The themes covered in the series include adolescent learners in India, titles in subject pedagogies (English, Mathematics, Science and Social Science), knowledge and learning, ICT and new media in education, and state, education and policy.

Each book covers key concepts, constructs, theories, conceptual and empirical frameworks and contemporary discourses around the topic. The content and discussions are meant to broaden and deepen readers' understanding of the topic. Cases, narratives and vignettes are used for contextual illustration of ideas. It is desirable that educators bring supplementary illustrations to problematise local issues. The references, range of activities and discussion triggers provided in each volume are meant to enable readers to explore issues further. The books are meant to be used as one among many 'resources' rather than 'a textbook'.

Additionally, with the purchase of the books in this series, readers can avail supplementary resources hosted on the TISSx platform, which can be accessed on this URL: https://www.tissx.tiss.edu/. Each book comes with a QR code on its cover that serves as a coupon to access the resources on this platform. Readers may follow these simple steps to reach the pages:

1. Click on https://www.tissx.tiss.edu/ taking care that the text is entered correctly. You can also scan the QR code on the cover of this book to access the website.
2. Register on the platform with a valid email ID by clicking on the 'Register' button on the top of the page. Fill in the details requested.
3. A verification link will be sent to your registered email address as soon as you register. Click on the link to activate your account.
4. You can now log in to the TISSx platform, and visit the e-resource page of the specific book/s you have purchased, through the link provided. Enrol in the relevant course by entering the coupon code provided (PBAT01) in the respective books.

It is hoped that this book series will help readers gain nuanced perspectives on the topics, along with relevant skills and dispositions to integrate into their teaching repertoire.

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FOREWORD

The discipline of education and professional development of teachers in India and the broader South Asian region has been undergoing radical redefinition over the last 30 years, with significant advancements in its conceptual base, approaches to theory and practice, and the formation of practice of teachers. Policy documents such as the National Curriculum Framework (2005) and the National Curriculum Framework for Teacher Education (2009) in India lay out for us the scope and depth of ideas that are of contemporary disciplinary interest. Resources that enable students of education to engage with these ideas relevant to the developing world contexts are, however, very few. This has been a key problem in widespread dissemination and for the ideas taking root in disciplinary discourses and practices in the university and colleges of teacher education. While planning the scope of work of the Centre of Excellence in Teacher Education at the Tata Institute of Social Sciences, seeded by the Tata Trusts, therefore, we included the development of resources as one of the major activities that will be needed in order to revitalise the sector. Dr. Mythili Ramchand and Dr. Nishevita Jayendran, as series editors, have laid out the scope and vision of such resources built around a series of textbooks to be developed in English and major modern Indian languages. Recognising the importance of such an initiative, several colleagues from universities in India have joined this effort as collaborators.

Textbooks are essential to support the formation and advancement of disciplines. Important scientific ideas became integrated into disciplinary thinking through textbooks written by scientists themselves. In the colonised world, textbooks came to represent 'colonisers' knowledge' and the cornerstone of the examination system, defining 'official knowledge' and strongly framing academic discourse from the world outside. Many of us trained in education, therefore, retain a suspicion of textbooks that may come to dominate the intellectual mental scape of students, and have sought out 'original writings' to include in our course reading compendia. Important as the reading of original texts is, particularly in the social sciences, they do not address what good textbooks can do and need to do for their students: performing a disciplinary landscaping function that is contextually relevant, drawing on contemporary research and practice, putting ideas to use as tools for thinking, scaffolding engagement and stimulating inquiry. In developing the textbooks in this series, authors have drawn on their experiences of teaching, research, reading and field engagement. We hope that faculty of education, students of education and teachers will all find the resources useful.

Padma M. Sarangapani

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ACKNOWLEDGEMENTS

First and foremost, we would like to express our gratitude to the Centre of Excellence in Teacher Education for providing us with the opportunity to write this book as a part of the series Principles-Based Adaptive Teaching. The excellent leadership provided by Prof Padma Sarangapani (Chairperson, CETE) and the constant encouragement of the series editors, Prof Mythili Ramchand and Dr Nishevita Jayendran, made this book possible.

We are thankful to Dr Deepika Bansal for providing support on content as well as for continuous monitoring for ensuring that the book is complete in all respects. We thank Dr Karen Haydock for creating a beautiful illustration for the cover page of the paperback and South Asia editions of this book and giving us permission to use her other illustrations.

We are grateful for the comments and suggestions provided by the reviewers, Dr Jayashree Ramadas, Ms Chaitali Ghosh, Dr Anusha Ramanathan and the external reviewer. It immensely improved the quality of the book. Initial discussions with Dr Ritesh Kunyakari and Dr Amit Dhakulkar have been useful.

We appreciate that teachers from certain schools, namely, Ms Sarita Gosavi and Ms Vinodini Kalagi from Anand Niketan (Nashik), Ms Sushama Sharma from Anand Niketan (Wardha), Ms Anagha Bivalkar and Ms Lara Patwanrdhan from Aksharnandan (Pune), provided interesting examples from their classrooms and assessment methods and gave us permission to use them in this book. Similarly, Chaitali Ghosh provided us with a blueprint used by the AEF's Arihant College of Education (Pune), and Vinay R.R. from Marathi Vidnyan Parishad (Pune) allowed us to use the English translation of their innovative question paper. We would also like to thank the schools, teachers, student-teachers and school students with whom we worked for all these years. Interaction with them provided many of the experiences and insights documented in this book.

We would like to acknowledge Anirudh Agarwal for helping us with the digital content and Ramesh Khade for providing support on graphics and formatting.

ABBREVIATIONS

ADT	Astronomy Diagnostic Test
AIIMS	All India Institute of Medical Science
AIPSN	All India People's Science Network
BEd	Bachelor of Education
CBSE	Central Board of Secondary Education
CLIx	Connected Learning Initiative
CSCL	Computer-supported collaborative learning
D&T	Design and technology
DLIPS	Diagnostic learning in primary science
DNA	Deoxyribonucleic acid
FCI	Force Concept Inventory
HPS	History and philosophy of science
HSTP	Hoshangabad Science Teaching Programme
ICT	Information and communications technology
IIM	Indian Institute of Management
IISc	Indian Institute of Science
IUCAA	Inter-University Centre for Astronomy and Astrophysics
IVF	In-vitro fertilisation
KWL	Know, want to know, learned
LPG	Liquified petroleum gas
LSLA	Large-scale learning assessment
NAS	National Achievement Survey
NASA	National Aeronautics and Space Administration
NCERT	National Council of Educational Research and Training
NCF	National Curriculum Framework
NEP	National Education Policy
NoS	Nature of science

NTS	National Talent Search
PChK	Pedagogical chemistry knowledge
PBL	Project-based learning
PCK	Pedagogical content knowledge
PISA	Programme for International Student Assessment
RNA	Ribonucleic acid
ROM	Read-only memory
SEDG	Sustainable Education Development Goals
SSI	Socio-scientific issues
STEM	Science, technology, engineering and mathematics
STS	Science, technology and society
TIFR	Tata Institute of Fundamental Research
TIMSS	Trends in International Mathematics and Science Study
TNSF	Tamil Nadu Science Forum
UDL	Universal Design for Learning
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UNICEF	United Nations Children's Fund
USA	United States of America
ZPD	Zone of proximal development

INTRODUCTION

Humans are unique in their quest to understand nature and to attempt to influence it to their advantage. In the stone age, human beings would have relied on instincts such as some plants being edible and others harmful or healing. They recognised patterns such as diurnal and seasonal cycles. They used stones and bones as weapons and tools. Slowly, these forms of understanding evolved into more systematic knowledge of natural philosophy and then science and technology. Several civilisations across the globe have contributed to the remarkable progress in science and technology at various points of time in the last 5,000 years. However, science remained a specialised endeavour to be pursued by a few until the turn of the 19th century. It became a school subject around the mid-19th century in Britain and around the late 19th century in the United States. Nonetheless, science was excluded from the school curriculum in South Asia during the colonial era. Science has been taught as a compulsory subject since the 1970s in South Asia (Ramadas, 2003). In India, science was made a compulsory school subject following the recommendation of the National Education Commission (1964–1966), popularly known as Kothari Commission.

Developing a 'scientific habit of mind' has been one of the foremost aims of science education since the time it was introduced as a compulsory school subject. In India, Nehru used and popularised the term 'scientific temper'. India is the first and only country to adopt scientific temper in its Constitution explicitly. According to Article 51 A(h) (42nd amendment in 1976), '[It shall be the duty of every citizen of India] to develop scientific temper, humanism and the spirit of inquiry and reform'. However, we are still far from achieving this goal. Despite science being a highly sought out subject due to promising career aspects, scientific literacy remains low (Raza et al., 2002). Systematic research is required to come up with different solutions which will work in diverse contexts.

DOI: 10.4324/9781003047506-1

Globally, s(cientists), psychologists and educationists approached the problem of improving science education sometimes independently, sometimes jointly. Two psychologists, Jean Piaget and Lev Vygotsky, profoundly influenced the field of education, which gave rise to two main approaches to research in science education. Piaget proposed that knowledge is generated through the interaction between an individual and their environment. Although he acknowledged the importance of the social environment around a child, he experimented with and proposed theoretical accounts for influences of the physical environment such as space and objects (both natural and artificial) on cognition. This led to the cognitive approach to learning science which served as a framework for many research studies and educational reforms. Identifying alternative conceptions and mental models among students and studying their problem-solving strategies are prominent examples of research areas in the cognitive approach. The Nuffield Science Teaching Project in Britain is an example of curricular reform based on a cognitive approach.

On the other hand, Vygotsky was particularly interested in the role of social factors which support learning. They include scaffolding provided by adults or older peers and cultural tools such as language, number system, calendars, etc. This led to a socio-cultural approach to learning science. This approach, too, was used as a framework for many research studies. For example, cross-cultural studies captured differences in thinking in different cultures (Samarapungavan et al., 1996; Mali & Howe, 1979; Klein, 1982). Interventions that included socio-scientific issues or encouraged peer learning and collaboration or emphasised the nature of science also stem from socio-cultural approaches.

We will discuss these two approaches (cognitive and socio-cultural) in more detail later in this book.

Pedagogical Content Knowledge

Psychologists have come up with guidelines for practices to enable learning with meaning, design assessments, ways to provide feedback and so on. Consequently, the curriculum for teacher preparation includes these practices. Science experts push for accurate learning of content and skills development required in science. Thus, there are two aspects to teachers' knowledge: Pedagogical knowledge and content knowledge.

The core scientific knowledge possessed by different professionals is the same. However, each field requires additional knowledge to use the scientific knowledge in a different context. If we take just one topic, say electricity, scientists, electrical engineers and electricians approach it differently. Scientists need to know the mathematical formulation and cutting-edge research in the field. Engineers need to know different applications of it and how to design new tools using the concepts. Electricians need to know the details of various electrical devices, understand what can go wrong with them and should be able to fix them. Similarly, teachers know the development of this topic across grades, other

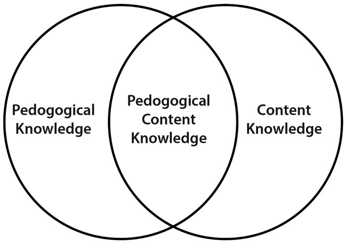

FIGURE 0.1 Pedagogical content knowledge is the kind of knowledge teachers need to possess in order to teach their specific subject effectively. Source: Illustration by Ramesh Prakash Khade.

topics that are connected to it (e.g., magnetism, energy, metals–nonmetals), students' difficulties while learning about electric current (they may treat electricity as a fluid rather than as a process), demonstrations and experiments which are effective in explaining the concepts (static electricity by rubbing two substances, Faraday's magnetic field induction experiment), appropriate assessment at different stages and so on.

This kind of knowledge is different from general pedagogical knowledge which can be applied while teaching any subject. It is also different from content knowledge alone (e.g., knowing Newton's laws or periodic table). In addition to these two types of knowledge, teachers need knowledge about how to teach their specific subject. This knowledge lies on the interface of pedagogy and content and hence it is known as 'pedagogical content knowledge' or PCK for short (see Figure 0.1). Since PCK has a component of content in it, the pedagogical content knowledge required to teach science is different from that required to teach mathematics or social sciences or languages.

Pedagogical content knowledge was first conceived by Shulman (1986) who argued that successful teachers have a special understanding of content knowledge and pedagogy from which they draw while teaching that content. Since then it has been used as a prominent framework to both understand and help form the knowledge base for teaching. A number of studies have used this framework to design interventions for teachers and student teachers. Other studies have found alternative conceptions in certain topics or best strategies to teach a topic which can feed into our understanding of PCK itself.

The PCK framework has been used to design this book so as to scaffold potential teachers' development of pedagogical content knowledge of science. PCK for science at the school level broadly includes understanding:

1. Why is science taught as a compulsory subject to all students? (*Aims of teaching science*)
2. What is science? What does it mean to learn science or to think scientifically? (*Nature of science*)

3. What are the different disciplines and how do they differ from each other? (*Nature of science and disciplinary knowledge*)
4. What are the major topics dealt with in each grade, how do they connect to each other and how does each topic progress across grade levels? (*Curricular knowledge*)
5. What are the major alternative conceptions in the discipline, how can they be dealt with, what demonstration, observations and experiments can be conducted to teach different concepts, what problems can be posed at each level, what are the representations used to express the content (text, diagrams, graphs, pi-charts, equations, models, simulations), what are their strengths and limitations, how are they connected to each other, what are the best ways to assess the knowledge? (*Cognitive approach*)
6. What cultural tools (e.g., Indian calendars to teach astronomy), stories/legends (Druva becoming a pole star, Lilavati, the mathematician), metaphors (heart as a pump) or examples from surroundings (chemical reactions in the kitchen) can be used to teach certain topics? What socio-scientific issues are related to each topic (stigma around menstruation, pollution caused by sanitary napkins or surrogacy, etc.)? (*Socio-cultural approach*)
7. What strategies and resources support inclusion in science classrooms? How can the teaching of each topic be made more inclusive (accessible to all students from different backgrounds, with different disabilities, etc.)? (*Inclusive approach*)

For each of the aspects mentioned above, the book draws extensively from research, literature on pedagogical interventions, reform efforts and policy documents. The book also uses a number of illustrative examples, cases from Indian classrooms, etc. based on the authors' own work as well as inputs from practitioners working in actual classrooms.

Organisation of the Book

The first chapter opens with a discussion on the aims of science education because that really determines the entire approach to science education such as framing the curriculum, adopting appropriate pedagogical practices and assessment. We go on to discuss a few curricular reforms and tried-out pedagogies in science education and close the chapter with the expected outcomes of science education. This chapter broadly aligns with the first and fourth aspects of PCK listed earlier.

To teach and assess science effectively, we must know what the essence of science is. What is the nature of science? Is there a scientific method? How is it different from other branches of knowledge? How do we validate scientific knowledge? These and other such questions are studied in philosophy of science. In the second chapter, we will have a short excursion into the realm of the history and philosophy of science. This chapter maps with the second aspect of PCK.

The subsequent three chapters introduce aspects of PCK in three disciplines studied at high school level, namely physics, chemistry and biology. The scope of each of these disciplines is quite large so we have restricted each discipline to illustrate one approach mentioned earlier. In Chapter 3, physics education focuses on the cognitive approach to learning science and in Chapter 5, biology education is elaborated from the socio-cultural approach to learning science. Please note that both the approaches (cognitive approach and socio-cultural approach) can be applied to any discipline. That is, the cognitive approach can very well be used for chemistry or biology education and the socio-cultural approach is perfectly suitable for physics. Chapters 3 and 5 give examples of classroom teaching based on these approaches. Chapter 4, along with introducing chemistry education, elaborates a prominent pedagogy in science education, namely 'inquiry-based learning'. Chapters 3, 4 and 5 align with PCK aspects 3 and 4 and in addition, Chapters 3 and 4 align with PCK aspect 5 and Chapter 5 aligns with PCK aspect 6.

In Chapter 6 we begin with examining assessment in general and then go on to discuss ways to assess students' learning in the area of science. It positions assessment as an integral part of the teaching-learning process rather than something over and above it. This chapter again aligns with PCK aspects 5 and 6.

Chapter 7 engages with one of the pressing issues in science education. Science is a powerful kind of knowledge and certain groups, because of their social, cultural, linguistic or educational background, have remained marginalised in learning science. In particular, sciences come across as an endeavour carried out by western men. Hence, it is important that girls and children who are culturally distant from western influences learn science in their own context, make it meaningful and own it! Sensory information is one of the main sources of scientific knowledge. Hence science poses a particular challenge to individuals with sensory disabilities. Making science learning meaningful for them is a challenge that science teachers have to address. Although concerns of equity and inclusion in science classrooms permeate across chapters, it is addressed specifically in this last chapter. This chapter aligns with PCK aspect 7. In the Appendix, we have offered some selected resources and tools which you might find useful in practice at the end of the book.

We hope that this book will give you an overview of the field of science education and help kindle the spark among your students! Suggestions from students, teachers, teacher educators and experts in the field are welcome. We will attempt to accommodate them in future editions.

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1

SCIENCE EDUCATION

An Overview

धैर्य दे अन नम्रता दे पाहण्या जे जे पहाणे
वाकू दे बुध्दीस माझ्या तप्त पोलादाप्रमाणे
जाऊ दे कार्पण्य 'मी' चे, दे धरु सर्वांस पोटी
भावनेला येऊ देगा शास्त्र काट्याची कसोटी.
– बा. सी. मर्ढेकर

Give me courage and humility to see whatever is to be seen.
Let my intellect be flexible as hot steel.
Let the stinginess of ego go away, let me embrace everyone.
Let rationality balance my emotion.
– B.S. Mardhekar

OBJECTIVES

The objectives of this chapter are to help you:

- understand why we teach science in schools.
- learn about the major efforts in science teaching across the world.
- learn about the two common ways of organising science curricula.
- learn different pedagogic practices used to teach science.
- discuss the outcomes of science education.

The chapter is organised as follows:

- Aims of Science Education
  - General Public's View on Science
  - Policy Documents
  - Science Education Literature
- Curriculum Organisations

DOI: 10.4324/9781003047506-2

    - Specific Science Content and Skills
    - Everyday Science
- Pedagogic Practices
    - Integrated Science
    - Project-Based Learning
    - Laboratory-Based Science Education
    - Using Information and Communication Technology to Teach Science
- Summary

Aims of Science Education

Across the world, science is taught in schools along with other subjects. Science has been perceived as so important in the modern world that we hardly think about why we teach science. What do children gain by learning science, and how will it benefit them and society in general? In this section, we will look at these questions and try to understand the aims and objectives of science education as stated by policy documents and literature from science education research. We will also contrast it with how the general public looks at science education.

ACTIVITY 1.1

Before reading further, stop here and make a list of the aims of science education according to you. Later while reading the sections below, compare your list with the list presented in this chapter.

General Public's View on Science[1]

Science is considered important for the development of the nation and solving problems. There is hardly any debate about whether science should be taught in schools or not. People may have different views on what should be taught in science and how it should be taught. Such is the image of modern science that it is taught as a compulsory subject till grade 10 in almost all Indian languages. When people talk about science they mostly do not differentiate between science and technology; for them, both are the same. So, when people say we should teach science, they also mean we should teach technology. Although science finds its application in technology, it must be noted that problem solving in science and technology follow different methodologies. To begin with, scientific inquiry is open-ended whereas, in technology, one must solve a practical problem. Designing plays an important role in technology whereas analytical thinking takes precedence in science. Indian curricula do not include much of design and technology (D&T) education, and researchers working in the area of

D&T education have been proposing it. It will not only encourage students to apply scientific concepts to solve practical problems but will also expose them to designing, which is a very creative process.

People also feel that current science education does not prepare students for the workplace. Concepts and skills learned in school science do not have real-life applications. People do not see the use of many concepts in the work they do or in day-to-day life. They feel that the only use of learning such concepts in school is to score good marks in examinations and nothing else.

More subtle aims of science education, discussed later, such as science for democracy or cultivation of scientific temper, do not find much space in public discourse. Unlike in the west, in India people do not see science in conflict with their religion and belief system. People have a utilitarian approach to science. An extremely small section of society uses scientific temper in their day-to-day decision making. This is not to say that science has not impacted Indian society; it has had a significant impact but science is yet to cover a lot of ground.

In this section, we saw what the general public thinks about science and science education. In the subsequent sections, we will look at policy documents and research literature and try to understand how these documents define the aims and objectives of science education.

Further Reading

Sarukkai, S. (2014). Indian experiences with science: Considerations for history, philosophy, and science education. In M.R. Matthews (Ed), *The International handbook of research in history, philosophy and science teaching*, Dordrecht, Springer, pp. 1691–1719.

Policy Documents

What is the aim of science education? To answer this question, according to the National Curriculum Framework (NCF) (2005), we should first ask: What is the goal of education? Why are we sending our children to schools? What do we want them to learn in school? There can be many answers to these questions, but the NCF (2005) argues that Gandhi was right when he said, 'True education is that which draws out and stimulates the spiritual, intellectual and physical faculties of the children'. Gandhi envisioned education's transformative role in an individual's life. Extending it to the role of science education, the NCF (2005) focus group on science education argues that it should also have a transformative effect on students' lives. To understand how science education can have such an effect on students' lives, we need to find out what is so special about science. What is it in science that has the potential to positively impact students' lives? What is the nature of science? In the second chapter of this book, we will learn about the nature of science in detail.

The general aims of science education follow directly from our understanding of the nature of science and technology as recommended in the current curriculum (NCF, 2005) and education policies (National Education Policy, 2020). They are as follows (National Council of Educational Research and Training [NCERT], 2007; Government of India [GoI], 2020).

A) Learn the Facts and Principles of Science

Students should learn some basic facts and principles of science; they should also learn its application. These facts and principles should be taught at an appropriate age that is consistent with the stage of cognitive development. This is to say; we should consider the research on cognitive science and check if the facts and principles we plan to teach can be understood by students given their stage of development. For example, we should provide young children (primary grades) opportunities to deal with the concrete world rather than the abstract world. So teaching abstract concepts like energy, chemical bonds or evolution would be inappropriate at a young age.

B) Skills and Methods of Science

Scientists use some specific skills and methods when they generate knowledge, such as generating hypotheses, controlling certain parameters while systematically varying others, observations and measurement, analysing data using graphs and statistics, drawing inferences, ruling out alternative explanations and so on. Students should acquire at least some of these skills and learn about the methods and processes in science. Students should know how the facts and principles mentioned in the above points are generated and validated. How does the scientific community accept something as a fact, and how does it resolve conflicts when there are competing hypotheses?

C) Science as a Social Enterprise

Science education should help students understand the social nature of science. They should know that scientists are human beings, and science is affected by socio-political environments. They should also learn about self-correcting measures such as triangulation of data from multiple sources, mathematical consistency, replication of experiments by different groups, peer review, collaboration, etc., which got developed over the years to maintain hygiene and ensure the integrity of knowledge. To understand it, students should be given an opportunity to study the history of science and see how science has developed over the years and will continue to develop in future.

D) Understand Science, Technology and Society (STS) Issues

Students should learn that every scientific or technological development affects society, the effects can be both positive and negative. For example, pesticides and fertiliser have increased food security in many parts of the world but at the same time, they have greatly contributed to soil and water pollution and ended up killing certain important organisms in the food chain such as bees and birds thus upsetting the balance of the ecosystem. Similarly, on one hand, the electronic revolution has greatly improved our communication and access to knowledge, on the other hand, it has given rise to electronic waste. Students should develop an ability to see the larger picture and understand the consequences of any scientific or technological venture so that they will be able to critically assess the complex issues new technologies can create and make informed choices in future.

E) Prepare for Work

Science education should equip students with knowledge and skills so that they can join the workforce working in STEM fields after finishing their education. Along with knowledge students should have practical and technical skills to perform work in the real world.

F) Nurture Curiosity and Creativity

Human beings, especially children, are naturally curious. Children often ask very interesting questions such as: How does such a small cricket make such a loud sound? How does the sun keep burning if there is no oxygen in space? And so on. The enterprise of science too is born out of curiosity. Science education should nurture natural curiosity through the discipline of science by pursuing their questions systematically yet creatively. It should also help students develop an aesthetic sense to appreciate the beauty of nature.

G) Imbibe Values

Science education cannot be and should not be value-free, it should imbibe basic values like honesty, cooperation, concern for not just human life but life in general. It should help students understand the need and importance of conservation and preservation of the environment. Science also helps students to internalise scientific and epistemic values such as reliability, testability, repeatability, accuracy, generality, parsimony, novelty and so on (Allchin, 1999).

H) Cultivate Scientific Temper

The Indian constitution includes the development of 'scientific temper' as a constitutional duty. The term Scientific temper is unique to India and was formulated by first prime minister Jawaharlal Nehru. He defines it as 'the refusal to accept anything without testing and trial, the capacity to change previous conclusions in the face of new evidence, the reliance on observed fact and not on the preconceived theory' (Nehru, 1946). Science education should help students develop scientific temper which includes, objectivity, critical thinking and freedom from fear and any prejudice.

> **ACTIVITY 1.2**
>
> The aims of science education mentioned in this section are not mutually exclusive; in fact, they are interconnected. Try to draw connections between the different aims listed here.

In the next subsection, we will discuss the aims of science education as proposed by the international community of researchers working in the area of science education.

Science Education Literature

Researchers have been studying the teaching and learning of science in schools and colleges. Along with how to teach science they have also looked at why we teach and learn science, what are and what should be the aims and objectives of science education and how to evaluate whether the aims are met. The research on the aims and objectives of science education has an impact on the policy documents discussed in the previous section but everything from the science education literature doesn't find a place in policy documents – mostly because the literature in science education is continuously evolving and policymakers have a different focus as compared to science education researchers. That is why it is important to look at science education literature and understand what aims and objectives of science education are important for the research community. In the following subsections, we list a few most important and prominent ideas from literature.

A) Scientific Literacy

Scientific literacy is one of the most important and common ideas talked about in science education literature in the context of discussing the aims of science education. Most of the researchers agree that science education should make students 'science literate', but there are different conceptions of what scientific literacy means. Roberts (2007), after a comprehensive review of the conceptualisation of scientific literacy by various researchers, came up with two broad categories. According to him, the researchers propose two visions of scientific literacy, Vision I and Vision II. As per the proponents of Vision I, the primary aim of science education is to teach basic scientific concepts and processes, helping students understand the process of generating scientific knowledge and learn about the skills and processes used within the sciences.

Meanwhile, the proponents of Vision II argue against the teaching of decontextualised science concepts and ask for helping students understand and use science in context and situations outside the traditional boundaries of science. These can be 'real-life' situations students face in daily life, situations where along with scientific considerations, other perspectives also come into play. Perspectives such as social, political, ethical, economic and moral can play an important role and also blur the boundaries making it difficult to understand when scientific considerations end and social or ethical considerations start (women's right to abortion is one such topic, assisted suicide is another). Vision I looks within the discipline of science to understand what a scientifically literate person should know and should be able to do, whereas Vision II looks for situations that present opportunities for a scientifically literate individual to use scientific ideas, processes and skills. In the last section on pedagogical approaches, we will see how these two visions translate into two different kinds of pedagogic practices.

ACTIVITY 1.3

Take the science textbooks designed by various state boards (at least three, many of them are available online) and compare them to see if they fall under Vision I or Vision II of scientific literacy described here.

B) Science for Social Justice

Many researchers believe that science education in schools and colleges should help achieving social justice. For example, science education should help in challenging social issues such as racism or casteism or classism. Barton's (1998, 2001) work with homeless children in the USA has shown that students' active participation and meaningful learning happens when students believe that their work can make a difference to their lives and the lives of their family members and friends. Barton and others were successful in showing that the students who are considered academically poor were able to do real scientific work given the real choice to work and believed that their work can affect their lives. Along with Barton, Hammond (2001) and Roth and Désautels (2002) have shown through their work that we cannot think of science education in isolation, scientific literacy is also linked with social and political literacy. We should broaden the aim of science education and include social justice in it.

India has seen many public science movements which are democratising access to science and also satisfying the curiosity of the masses (Venkateswaran, 2020). Children and the public get access to these alternative mediums depending on the reach of the medium and the socio-economic status of the people. All India People's Science Network (AIPSN) is a network of many people's science movements; it has reached across India through various member organisations and has been playing an important role in satisfying the curiosity of the people by organising events and programmes like Joy of Learning (1994), Cosmic Voyage (1995), People's Reading Movement (1995), International Year of Astronomy (2009), Eyes on ISON (2013), Solar Eclipse Festival (2019), etc. (Venkateswaran, 2020).

C) Criticality

There is no doubt that critical thinking is important. This is recognised by the NEP (2020) as well (GoI, 2020). Criticality is going one step beyond critical thinking (Reiss, 2007). According to Oulton et al. (2004), criticality is using the product of critical thinking to bring social change. Olton and his colleagues argue that both students and teachers should not only look at others' stances critically but should also examine their stance with a critical eye. They also think that in a classroom discussion while discussing a controversial topic a teacher should not take a neutral position but share his actual position on the topic. In such a class, they argue, students would reflect on all the positions and arrive at their own conclusions. The teacher's stance won't influence students' thinking if the students have learned to think critically. It will motivate teachers to openly discuss controversial topics with students. A lot of work in this area is inspired by the seminal work of Paulo Freire (2018) where the teacher is not just a neutral-meek spectator but an agent of change who is capable of helping in transforming social conditions through action as a result of critical thinking.

D) Democracy

In a democratic country, citizens play many roles and perform many duties, ranging from voting in elections to evaluating and protesting for/against laws. In democracies, leaders, governments and organisations use science to justify and support their arguments, which makes it necessary that the citizens are in a position to understand the scientific ideas being used by leaders and governments. As mentioned earlier in the section on scientific temper, citizens can perform their duties and roles better if they use the scientific thought process which involves not accepting anything without analysing it critically, if possible testing and trying, accepting something due to evidence and not because of preconceived notions. Researchers like Longbottom and Butler (1999) argue that the primary aim of science education should be to create citizens who can contribute to the advancement of a democratic society.

E) Sustainability

The continuous push of material development has caused enormous damage to the planet and life on the planet. There is a global call to rethink the model of development and opt for models of development that meet the needs of present generations but do not put the lives of future generations in danger. Almost everyone agrees that we need sustainable development and many believe that the aim of education and science education should be to create the awareness needed for sustainable development. Science education can create individuals who can think critically, apply learning from a context to new situations, think creatively and solve problems, adjust society and alter habits needed for sustainable development (Akpan, 2017).

ACTIVITY 1.4

Talk to a few (at least three) people you know who do not work in science-related fields. Ask them what the aims and objectives of science education are according to them. Why do we learn science in schools? What do they think school science education is expected to achieve? Note their responses and compare them with points in the next section; see if you can get some responses that are not listed in the following.

Curriculum Organisation

The choice of organising curriculum follows the aims and objectives of science education. We have listed many aims in the earlier sections but when curricula are designed not all aims need to be considered and given equal importance. Out of all the listed aims, different curricula give importance to different aims and objectives and it affects the choice of the pedagogic practice. If the aim is to prepare a future workforce, then the curriculum should help students acquire content knowledge and skills required for working in a science-related field. But the same curriculum won't prepare students for citizenship roles. It doesn't mean that for each listed aim there is a separate curriculum approach or a corresponding pedagogic practice; the various aims are interrelated. For example, if the aim is to make students think critically then it also means that students will learn to use critical thinking in taking actions for achieving social justice, performing democratic roles and achieving sustainable development. Broadly all the listed aims fall into two major categories as discussed in the section on scientific literacy, Vision I and Vision II. These two visions prescribe two different curricula. In the following subsections, we will look at those two curricular approaches.

Specific Science Content and Skills

Historically this has been the most common curricular approach around the world to teaching science. The approach is based on the belief that a good science education teaches students important scientific and technical skills which are commonly used in scientific workplaces – skills like designing and conducting experiments, handling commonly used tools in science labs, repeating the landmark experiments and observations in science, collecting data and analysing the data. Along with skills, important concepts from each field are selected and taught to the students. For example, in physics laws of motion, in chemistry gas laws or in biology Mendel's laws. These concepts are selected because they are central to the subject and it is believed that if students learn those concepts they will also understand the basic ethos of the subject. Teaching these specific concepts and skills is also aimed at preparing students for future work.

Everyday Science

The basic criticism of the previous approach is that not everyone who enrols in school is going to choose a career in the STEM field. A very small percentage of students will enter the scientific field whereas others will opt for a variety of non-science fields. So using a curriculum that prepares students for future science-related work is not a good idea. Also, the research has shown that the traditional curricular approach to science education cannot prepare students for citizenship roles, to use science in solving everyday problems, or to achieve social justice (Feinstein, 2009). Then isn't it sensible to organise curriculum so as to teach 'everyday science' in schools, as every student would need these skills including those who are going to join the scientific workforce in future? At a later stage, some students may opt for science specialisation to go in for a career related to science.

In this approach to organising science curricula, concepts and principles are chosen because they are close to the real-life of students studying it. This is in contrast to the previous approach where concepts and principles are chosen to be taught because they are central to the discipline (biology or physics) being taught. People encounter various challenges in their day-to-day life; many of the challenges have scientific components to them, as in the case of a government policy that claims to be based on scientific study or choice of medicines. The everyday science approach prepares students to solve problems like these. If students learn how scientific knowledge is produced, validated and communicated they will be able to read the scientific study used to justify the policy and check the government's claims. Everyday science approaches equip students with skills so that they evaluate claims made by, say, homoeopathy and allopathy. They can check the evidence given to support the claims made by two types of medicine. Students could ask: Can something so diluted that it can't be deducted cure some illness? Can such a medicine pass the placebo test? Good science education with a focus on everyday challenges would prepare students to ask such questions and make their judgements.

The aims of science education not only dictate what we choose to teach (curriculum) but also how we teach it. In Chapters 3, 4 and 5, we will see examples of three prominent approaches, namely, cognitive approach, inquiry approach and socio-cultural approach. We will also see how they can be used to teach various topics in different subjects. We introduce a few other pedagogic practices here.

ACTIVITY 1.5

Take a science textbook for any grade between 5 and 10. For each chapter identify whether the main focus is on developing science content and skills or on everyday science. Try to identify a broad curricular approach based on which the textbook is written.

Further Readings

Feinstein, N. (2009). Why teaching "everyday science" makes sense. *Phi Delta Kappan*, *90*(10), 762–766.

Campbell, B., & Lubben, F. (2000). Learning science through contexts: Helping pupils make sense of everyday situations. *International Journal of Science Education*, *22*(3), 239–252.

Pedagogic Practices

The same curriculum can be taught using different pedagogic practices. For example, a teacher can take an instructionist approach and give a lecture on an ecosystem and its components, whereas another teacher can take a project-based learning approach and use a project to help students learn about an ecosystem, its components and dynamic interactions among them. The choice of pedagogic practice plays an important role in students' learning. Some pedagogies are better than others and some are more suitable for certain topics than others. A teacher has to choose the most suitable pedagogy for a given topic based on the content, her knowledge about the strength and limitations of the pedagogies, students' prior understandings and her previous experience. The choice of pedagogy is a reflection of a teacher's PCK. A number of pedagogic practices have been proposed in science education literature. However, we will discuss four pedagogies that have been influential in science education literature or have been tried out in India.

Integrated Science

Our school curricula for natural sciences mainly represent three disciplines, namely physics, chemistry and biology. But the scope of each discipline is so vast that many of the branches of the disciplines such as ornithology[2] and meteorology are left out. Moreover, disciplines on the interface of natural sciences and social sciences (e.g., archaeology, psychology, linguistics) do not find a place in the curriculum.

How do birds fly? How does snake poison affect our bodies? Why is it a good practice to rotate the crops? How do we determine which is a better fuel between, say, petrol and LPG? How did petroleum form in the crust of the earth?

What causes Down's syndrome? These and many such questions fall on the interface of two or more disciplines. When a question arises in a curious mind, does it heed the disciplinary divide of science? Can nature be neatly organised into disciplines? No! The heart is run by electric pulses and the plants make their food by photosynthesis. In fact, real-life problems require information from multiple disciplines, including those in social sciences. For example, to answer questions such as why India is the second most affected country in the world by diabetes will require information about genetics, causes of diabetes as well as lifestyle and recent history of the Indian population.

Project-Based Learning (PBL)

As the name suggests, in this pedagogic practice, students learn by working on a project for an extended period of time. The project is driven by an authentic, complex and challenging problem or challenge. While solving the problem or completing the challenge students had to perform activities such as brainstorming, information gathering, designing, analysing, communicating, collaborating and so on. These activities help students learn concepts and develop skills. For example, the teacher gives a design problem which is to redesign the playground in your school to make it safer and accessible for everyone. Or create a map of plants and animals on the school campus. In PBL students work in small groups, to answer a question or design challenge they create a project plan, divide the activities they'll be doing, create a schedule of activities. The teacher takes the role of facilitator and helps students by posing the problem at the beginning and posing questions during the activity. The teacher also provides support material in terms of rubrics, readings, raw data, guidelines, etc. Depending on the problem or challenge or questions, students' projects can last from a few hours to a few days. Students' investigations do not limit themselves to any one subject or topic, they go wherever their questions take them. A science project can lead students to subjects other than science, such as history, mathematics or social studies. For example, designing a safer and accessible playground may push students to think about accessibility as a social issue or they might look at disability as a form of oppression. They will also have to do a lot of calculations while designing a playground that would take them to mathematics. PBL is a multidisciplinary approach, students learn about various topics from different subjects in the course of completing the project and develop skills such as problem solving, collaboration and project management. It also nurtures creativity, curiosity, perseverance, in-depth understanding and self-confidence.

As mentioned above pedagogic approaches have strengths and limitations, PBL also has limitations such as it is very difficult to use in large classrooms, it cannot be applied to every teaching-learning situation or process. Sometimes it becomes too costly in terms of time and resources compared to other pedagogical approaches. Sometimes it becomes difficult to maintain students' motivation level throughout the project and that can affect the intended learning outcome. In some cases, assessment of the learning becomes challenging as everything cannot be measured. As the output is a solution to the problem or question or challenge, students do not always articulate their learnings explicitly which makes it harder for the teacher to assess the learning. Teachers need to support students by guiding or leading questions during the projects and sometimes it can become difficult to maintain the balance between giving too much support or not giving enough support. Making both mistakes can hamper the learning process.

Laboratory-Based Science Education

Experimentation is one of the main pillars of science. Naturally, it should find a prominent place in science education as well. This pedagogic approach does that, in it, the experimentation takes the central place. Teachers use experiments as context to illustrate concepts or a phenomenon or to give their students an experience of the scientific process (Duit & Tesch, 2021). Experiments can be of different types; some can be just demonstrations (example – demonstrating static electricity), some can be simulations of famous experiments (example – asking students to perform a rolling ball experiment to calculate velocity) and some can be open-ended investigations (example – find out the reason behind the death of plants in the school garden). Each serves a purpose in science teaching and learning. The teacher chooses the type of experiment depending on the time available, nature of the activity and students' safety. Experiments make learning activities hands-on, teach science processes and skills, explain the philosophy of science issues, illustrate the significance of science and technology in everyday life, arouse the interest of students and encourage them to perform experiments on their own (Duit & Tesch, 2021). Open-ended experiments have the potential of developing science-specific skills mentioned in section 'Skills and Methods of Science' – skills like using the scientific method to solve day-to-day problems, find answers to questions or create innovative solutions. Experiments have a role in both visions of scientific literacy mentioned above, be it learning about science or using science to solve problems outside science.

BOX 1.1 REFLECTION ON 'SHOW AND TELL' APPROACH TO SCIENCE EXPERIMENTS IN CLASSROOMS

Read this excerpt from Padma Sarangapani's conversation with a middle-school student, Joni. Reflect on the 'show and tell' approach to science experiments in classrooms.

PS: Why do you do experiments in Science?
J: They say 'do this', 'do that'. Tomorrow you come to my house. I will show you an experiment. Take a tumbler. Crush a paper and put it into it … (He described the common experiment to prove that air exists and occupies space.)

PS: Where did you learn it?
J: Kanta madam did it and showed it to us.
PS: Why did she do it?
J: Don't know.
PS: What did you learn from it?
J: (Shrugs.)

Joni was describing an easy and elegant experiment that suggests that what we think is 'empty' space has something which we cannot see or feel: it occupies space and can exert pressure. The conclusion involves interpreting the unexpected findings of the experiment – that water does not fill up the glass and the paper remains dry. The observation is not self-explanatory. Joni's understanding of the experiment was just the activity, without any interpretation. This doing was identified as what constitutes an experiment.

Source: Sarangapani, P. 2003. Constructing School Knowledge. *Sage Publications, India, p. 221.*

Even though experimentations are considered important in science and have the aforementioned benefits for teaching and learning science we do not see the use of this approach commonly in Indian classrooms. Experiments are costly in terms of time and resources and that is one reason why they are not commonly used in science classrooms. Safety is another reason why experiments are avoided. In the next subsection, we will discuss how new media can make experiments in science classrooms possible.

Using Information and Communication Technology to Teach Science

Information and communication technology, or new media as it is often called, has certain advantages over traditional media. These advantages can be used to teach and learn science. Some of the advantages offered by the new media are, collaboration in virtual space, externalisation of memory and mental processes, supporting visualisation and imagination and providing multiple external representations. In this pedagogical approach, the aforementioned advantages are exploited in learning science. For example, networked computers (internet or local network) create a space for collaboration that is flexible in terms of time and space. Learners can collaborate even if they are not in the same physical space or same time zone. The teacher can provide material or ask questions and students from anywhere in the world can respond and that too whenever it is possible for them.

ACTIVITY 1.6

Computer-supported collaborative learning (CSCL) is a field of research that studies learning supported by new media. Read more about CSCL on the internet, make a list of advantages it has and think about possible ways of using it in your classroom.

New media tools such as simulations, animations, models and videos are used in teaching and learning science as it supports students' visuospatial thinking. For example, students struggle to understand the evolution or dynamic interactions of components of an ecosystem as they are extremely slow and cannot be seen directly. They have to be inferred from the observations. New media approaches can be very useful in such cases. Simulations created using platforms like NetLogo or StarLogo can be effectively used to show the slow and dynamic processes such as evolution. Simulations allow students to take control of these processes, change speed, change variables and try out different imaginary or real situations. For example, while teaching about the ecosystem and its components a teacher can ask students to play with a simulation on the NetLogo platform. Students can play with simulations of a fish farm. The simulation has a model of a fish farm in which we can select the initial number of fishes and their hunger rate and an initial number of algae and their reproduction rate. Then we can run the simulation, algae start reproducing with the speed specified by the student and fishes start eating algae depending on the hunger rate specified by the students. Simulations show a graph of the number of algae and fishes over time and a student can see how the number is changing over time. Depending on the initial parameters selected by the student either fish will first eat all the algae and then die of hunger or the number of algae will first increase exponentially then the number of fish will increase as there is more food and it will keep fluctuating between two extremes. Or in another case, it will be relatively balanced situations where algae number is just enough to sustain a stable fish population. When students see this they will realise that the components of an ecosystem interact with each other and the interactions are dynamic. A static diagram can never capture the dynamic nature and it creates hurdles in students' learning.

New media tools also provide a safe space for performing science experiments. Many experiments cannot be performed in the science classroom as they are not safe or the resources are not available or cannot be performed in a school setting. New media tools can be of great help in such situations. For example, it is not possible to perform the famous thought experiment suggested by Galileo where he proposed that both a feather and a metal ball when released from a tower should reach the ground at the same time. Even Galileo was not able to perform this experiment as resistance by air interferes and one would need a vacuum chamber to perform the experiment. But in a virtual physics lab, we can easily perform such an experiment. Similarly, many experiments involving dangerous chemicals cannot be performed in school due to safety reasons but virtual chemistry labs provide a safe space for students to perform experiments.

The new media approach has gained a lot of popularity in recent years; everybody is talking about it and with advancement in technology, access to technology is becoming more and more possible with each passing day. But still for a country like India, making computers available for every school student is a distant dream. Teachers should keep themselves updated with the latest happenings related to this approach so that they can use it in their teaching whenever it is possible. In the next section, we will discuss the possible outcomes of various curriculum and pedagogic approaches.

ACTIVITY 1.7

Explore any two simulations from the following platforms:

1. NetLogo: https://ccl.northwestern.edu/netlogo/
2. Phet: https://phet.colorado.edu/

Further Readings

Stahl, G. (2006). *Group cognition: Computer support for building collaborative knowledge (acting with technology).* The MIT Press.
Nawani, D. (Ed.). (2016). *Teaching learning resources for elementary school*. Sage.

SUMMARY

In this chapter, we learnt:

- Some of the important aims and objectives of science education, which are to:
  - learn the facts and principles of science.
  - develop skills and learn the method of science.
  - understand science is a social enterprise.
  - understand science, technology and society (STS) issues.
  - make students scientifically literate.
  - equip students with knowledge and skills so that they can use science for social justice.
  - develop critical thinking and criticality in students.
  - prepare students for democratic roles.
  - make students aware of the need for sustainable development and help them think about it critically.

- Many people do not differentiate between science and technology, but these are separate enterprises although closely linked.
- Science education for democracy, social justice, scientific temper, etc. do not find a place in public discourse around the aims of science education.
- There are two major categories of curriculum organisation; the first one focuses on teaching specific content and skills because they are central to the various subjects in science.
- The second approach focuses on teaching content and skills that are central to the lives of the students who are learning science and in the future will face such challenges. This approach is broadly called every-day science.
- There are a variety of pedagogic practices that teachers can adapt, depending on their PCK.

Exercises and Practice Questions

1. Discuss the aims listed in the chapter with your friend and together reflect on science teaching you have experienced and observed. How many aims listed in the chapter are being realised and which are those?
2. Take a science textbook of any grade at the high school level and analyse it to see if it falls under Vision I or Vision II of scientific literacy. Justify your categorisation.
3. Take any two pedagogic approaches and write advantages and limitations of them.
4. Choose a topic from secondary school science. Prepare a plan to teach the topic using any one of the four pedagogic practices described. Justify your choice of pedagogy.
5. Talk to some secondary school students and find out what they are curious about. Record their questions. Analyse if the science curriculum is able to satisfy their curiosity. Why/why not?
6. Imagine you are a science curriculum designer. What aims of teaching science would you decide upon and why? Discuss your response with a friend. If both of you were present on the curriculum-designing committee, how would you negotiate the process of making the curriculum? What compromises will each of you make to design a coherent curriculum document?
7. According to you, what should be the aims of education (in general)? Compare these aims with the aims of science education listed in the previous question. What are the similarities and differences between them? Do you think all the aims of education can be met by designing science education in a certain way? Justify your answer and discuss your response with your friends.
8. Some policymakers suggest that formal science education should focus on improving the performance of students on international tests such as PISA

(Programme for International Student Assessment). Do you agree with this suggestion? Give reasons for your response. Divide the class into two groups and have a debate on the topic.

Notes

1 This subsection is written based on interviews conducted by students in science education courses. Their names are Smriti Shovna, Diksha M.A. and Deepak Arora.
2 Branch of zoology that studies birds and everything related to them.

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2

NATURE OF SCIENCE

எப்பொருள் எத்தன்மைத் தாயினும் அப்பொருள் மெய்ப்பொருள் காண்பது அறிவு. epporuL eththanmaith thaayinum apporuL meypporuL kaaNpadhu aRivu. – திருவள்ளுவர்	Whatever be the thing and whatever be its nature, wisdom is to find its true nature. – Thiruvalluvar, kural 355

OBJECTIVES

The objectives of this chapter are to help you:

- recognise nature and elements of scientific knowledge.
- understand different practices associated with science.
- appreciate that science is a particular way of looking at the world.
- analyse critically the values associated with science.
- identify science as a human and institutional endeavour.
- evaluate the relationship between science, technology and society.
- design lessons to teach nature of science to secondary school students.

The chapter is organised as follows:

- Scientific Knowledge
    - Ideas about Scientific Knowledge

DOI: 10.4324/9781003047506-3

- Ideas about the Truth of Scientific Knowledge
    - Current Ideas about Scientific Knowledge
    - What Differentiates Scientific Knowledge from Other Domains
    - Science, Common Sense and Pseudoscience
    - Elements of Scientific Knowledge
- Scientific Practices
    - How is Scientific Knowledge Generated?
    - What is Scientific Inquiry?
    - Inquiry in the Science Classroom
    - Exclusionary Practices of Science
- Scientific Enterprise
    - Institutionalisation of Science
    - Science as a Human Endeavour
- Scientific World View
- Values Associated with Science
    - Science and Technology
- Education for Nature of Science
    - Why Study Nature of Science
    - Tenets of Nature of Science
    - Integrating NoS in Science Classrooms
- Summary

Scientific Knowledge

ACTIVITY 2.1

List ten features that you would associate with 'science'. Compare the list with that of your classmates. How many features are common across your lists? What are some of the unique features that were listed?

Science is considered to be a systematic search for knowledge (Appiah, 2003; Dewey, 1903). In fact, it is taken to be a 'standard model' for knowledge and truth (Sarukkai, 2012). However, truth and knowledge are both complex constructs and there have been different perceptions and contestations around the nature of scientific knowledge and truth. Along with the growth of the discipline of science, these ideas 'about' science have been emerging from philosophy, sociology and more recently education. Currently, there exists voluminous literature on the topic (Phillips, 1985). It is neither possible nor relevant to summarise it in this section. To help teachers of science appreciate the complexity of the nature of scientific knowledge, a brief outline of some of the ideas emerging from literature are described in this chapter.

Ideas about Scientific Knowledge

For the most part of the history of modern science, the certainty of scientific knowledge was taken for granted. This certainty gave rise to the belief in a 'scientific method'. It is considered as a set of rules of procedure that scientists follow that leads them to secure knowledge (Hoyningen-Huene, 2013). Galileo Galilei (1564–1642), Francis Bacon (1561–1626), René Descartes (1596–1650) and Isaac Newton (1642–1727) are some of the examples that are held as prototypical of devising and following the scientific method. However, developments in modern physics in the early 20th century and emerging ideas from the sociology of knowledge indicated that scientific knowledge was fallible and primarily constructed by scientists (Longino, 1990). The fallibility of science and the constructivist theory of knowledge by no means imply that scientific knowledge is undependable or that science is no different from other forms of knowledge. Science continues to offer the best rational explanations of the natural world through systematic studies and reasoned publicly defensible judgements of researchers (Phillips, 1985). While those who adhere to what is known as 'scientism' continue to believe in one method essential to science, the current characterisation of scientific methods recognises their diversity and argue for a contextual understanding rooted in actual scientific practices (Hepburn & Andersen, 2021). It is not that the methods employed are unique to science, but that the methods are more systematically employed in science (Hoyningen-Huene, 2013).

BOX 2.1 REFLECTION ON THE NATURE OF SCIENTIFIC KNOWLEDGE AND METHODS OF SCIENCE

Reflect on the nature of scientific knowledge and methods of science as you read the following narrative.

How the First Periodic Table Evolved

The Russian chemist Dmitri Mendeleev created the periodic table for his book *Principles of Chemistry*, published in 1868. There was little systematic understanding of the data available on elements at that time. So Mendeleev started collecting all available data on every known element to see if there was any 'periodic' (regular) order. On his laboratory wall, he began cataloguing the data. He listed the sixty-three known elements on cards arranging and rearranging them on the wall. On each card, he noted the atomic weight and other properties of that element, along with its known compounds. After many trials and errors, he worked out a system of rows and columns which reflected chemical and physical similarities between groups of elements. He set hydrogen in a special place because of its unique properties. Mendeleev arranged the next-seven known elements from lithium to fluorine in sequence of their increasing atomic weights in the first row. In the second row he wrote the next seven, from sodium to chlorine, and so on. The periodicity of chemical behaviour was obvious from the first two rows. Mendeleev went further and predicted the existence of elements that were not yet discovered by leaving gaps on his table. Chemists discovered these 'missing' elements over the next fifteen years.

(Lapp, 1969: 35)

Ideas about the Truth of Scientific Knowledge

Truth in science relates to facts of the natural world (Sarukkai, 2012).[1] While there are many contentions of truth, there are broadly two opposed criteria for determining truth. One camp considers that the evidence for the truth of scientific knowledge is provided by nature. This theory of truth is called realism. The other group holds a theory of social constructivism which contends that there can never be an 'objective' truth out there and truth is at best a consensus among scientists (Eflin et al., 1999). It is now widely accepted that what a scientist observes is mediated by his/her/their theoretical understandings and background knowledge. Again this is not to say that scientific knowledge cannot make any truth claims. As D.C. Phillips points out, because an observer looks at the world through theoretical frameworks does not mean nature is obliged to confirm that theory. The notion of truth as a regulative ideal in science means scientific knowledge converges towards the truth (Phillips, 1985). After all, science has produced innumerable truths about the natural world (Sarukkai, 2012). Rather than claiming evidence establishes the truth of a theory, truth of a scientific knowledge indicates the theory is consistent with the evidence that is currently available (Boyd & Bogen, 2021).

BOX 2.2 ANECDOTES FROM SCIENCE

Brewer and Lambert (2001) provide an example from astronomy about the theory-ladenness of observation.

> Among the first observations that Galileo made with his telescope were Jupiter's moons. In 1610, when he observed Saturn, he assumed what he saw were Saturn's moons. He was greatly puzzled to see them disappear two years later, only to reappear when he observed the planet again after four years. For the next fifty years, other astronomers continued to interpret their observations of Saturn with either moons or 'arms'. Christiaan Huygens was the first to propose a model of Saturn with rings in 1659.

> Before this model, even with improved telescopes, observers did not have a framework to make sense of the unfamiliar data.
>
> (Gregory, 1970)

Collect more such anecdotes from the history of science. What do they indicate about the criteria for determining the truth of scientific knowledge?

Current Ideas about Scientific Knowledge

There is consensus among science educators and philosophers of science regarding aspects of scientific knowledge, despite contestations around its complex nature. These include understandings that scientific knowledge is (AAAS, 1989; Eflin et al., 1999; McComas, 2002; Flick & Lederman, 2006):

- tentative (subject to change and revision).
- empirically based (derived from observations of the natural world).
- partially based on human inference.
- partially based on human imagination and creativity.
- subjective (data is collected and interpreted in light of current scientific perspectives as well as the experiences and values of individual scientists).
- socially and culturally embedded.

History of science indicates that science progresses both through the evolution of ideas and revolutionary leaps in uncharted areas (Kuhn, 1970). Kuhn termed each of these as paradigms. According to Kuhn (1970), the early stages of a new field of science are marked by various interpretations of observations and data. As the field grows, these differences largely disappear as the scientific community within the field agrees upon a certain paradigm as the 'correct' way to make sense of these observations (17). At a future point, a new paradigm may emerge, that overthrows the established explanations and interpretations of observations. Thus, scientific discovery often involves thinking about things in totally new ways. However, scientific ideas also build on one another. Modification of ideas and more nuanced and complex understandings emerging over a period of time, rather than outright rejection is what usually marks progress in science (Niiniluoto, 2019).

BOX 2.3 EVOLUTIONARY ASPECT OF SCIENTIFIC KNOWLEDGE

The history of the evolution of the concept of atoms offers a fascinating study of the evolutionary aspect of scientific knowledge.

The idea that matter is a collection of small, indivisible 'atoms' is more than two thousand years old, known both to the ancient Greeks and Indians.

But the idea was not taken seriously till John Dalton in the early nineteenth century. Dalton proposed each element is composed of one kind of identical atoms and that atoms combine in definite proportions to form molecules. That is the reason, for example, water always has the same ratio of hydrogen and oxygen. This was the conceptual revolution that established the basic atomic model chemists have used ever since.

Since the time of Dalton, our understanding of an atom has deepened and the concept has become enormously complex. Scientists have come a long way from the idea that an atom is the smallest, indivisible particle to probing inside an atom and studying unimaginably small subatomic particles. We can appreciate the scale at which scientists study when they probe inside an atom, considering that the diameter of an atom is around 0.0000005 mm. This means that it would take about 10 million atoms, arranged side by side, to fit into the eye of a sewing needle (Gamow, 1961).

Trace the evolution of a few other concepts and theories in science and reflect on how they have not only contributed to our understanding of the natural world but also helped free human consciousness from the stranglehold of superstitions and fear.

What Differentiates Scientific Knowledge from Other Domains

The question of differentiation has long been of interest to the community of philosophers of science. Karl Popper in his *Logic of Scientific Discovery* has engaged with this 'demarcation criterion' as one of the fundamental aspects of scientific knowledge. In his analysis, what differentiates science is its methods which require subjecting theories to rigorous tests. While the rigorous testing will not be able to establish the truth of the theory, it does give rise to a high probability of failing, thereby refuting the theory. Hence what is not falsified is taken as scientific knowledge at any given point in time (Popper, 1968). Communicating the descriptions and explanations of the tests and making the data available for public scrutiny is also what distinguishes science from other domains of knowledge. The language of communication that has distinctly evolved for science, since the time of Galileo and later Newton, is that of mathematics and a 'sterile', 'impersonal' use of a natural language like English or German, to ensure precision and avoid ambiguities (Sarukkai, 2012: 132). This specialised language combined with the tremendous increase in the quantum of scientific knowledge has rendered science inaccessible to those who are not specialists in the field. Science popularisation endeavours to make scientific knowledge accessible to the layperson.

Science, Common Sense and Pseudoscience

Aristotelian physics was largely built on common sense and endured for 18 centuries. The advent of modern physics proved many of the then–common sense knowledge insufficient or incorrect to account for understanding the natural world. A classic example is the motion of heavenly bodies which were taken to be true motions of the bodies. Copernicus established that what we observe are their apparent motions, which are the result of the true motions of the celestial bodies and our own motion as observers on earth. Some of the ideas established by modern science have now become common sense, such as earth's revolution around the sun. The difference between common sense and scientific knowledge varies across different fields of science. Hoyningen-Huene (2013) suggests it depends on the duration and the processes that went into altering or extending common sense understanding through scientific investigations and the field's subsequent progress in generating knowledge.

Whereas common sense marks an extension/break from science, pseudoscience is not science but masquerades as one. The philosopher Paul Thagard (1978) proposed a 'principle of demarcation' to differentiate pseudoscience from science. The features of pseudoscience include:

- little or no progress in knowledge over a long period of time.
- many unsolved problems.
- little or no attempts to evaluate a theory in relation to others.
- selectiveness in admitting evidence.

These distinctions are not always clear and uncontested. Nevertheless, we will adopt Dewey's contention that scientific knowledge as systematic is widely accepted (Dewey & Bentley, 1949). This systematicity applies both to the products of science, i.e., the scientific knowledge and the processes of science that have helped produce this knowledge (Dewey, 1903, quoted in Hoyningen-Huene, 2013).

Elements of Scientific Knowledge

Science has generated knowledge from the very small, at the scale of atoms and even smaller, to the very large, dealing with galaxies and their clusters. Science as a body of knowledge is often characterised by facts, concepts, principles, laws and theories.

ACTIVITY 2.2

Consider this example of a scientific knowledge that is fundamental to the discipline of chemistry.

The modern atomic theory was first formulated by John Dalton. The theory postulates that:

1. All matter is composed of atoms.
2. Atoms of the same element are the same; atoms of different elements are different.
3. Atoms combine in whole-number ratios to form compounds.

Which of these will be characterised as fact, concept, principle and law?

Table 2.1 gives a brief description of the elements of scientific knowledge.

It is often misunderstood that theories are lower in status to laws. Many individuals believe that theories become laws as they accumulate supporting evidence. But as we have just seen, theories and laws serve different roles in science and one cannot develop or be transformed into the other.

Further Readings

In the first chapter of his book *What Is Science?* the philosopher of science Sundar Sarukkai offers a range of ways for understanding science – as a concept, title given to a discipline, method, criterion for demarcation with other ways of knowing, inquiry, search for truth, way of thinking and doing, narrative, world view and means of controlling the world and politics.

Sarukkai, S. (2012). Defining science. In *What is science?* National Book Trust. Chapter 1.

Chunawala, S., Mahajan, B., Mahurkar, S., Natarajan, C., Ramadas, J., & Subramaniam, K. (2002). *The roots of reason: Science and technology in the ancient world*, In A. Kumar & S. Mahurkar (Eds.). Quest Publications.

Scientific Practices

ACTIVITY 2.3

Recollect the advertisements you have seen. How many of them claim to have scientific evidence to sell their products? Why do you think they do so? How many of these claims do you personally believe? Why or why not?

Design an investigation to test the claims of an advertisement for a soap detergent that claims to remove ink stains.

This section describes how scientific knowledge is generated, what is scientific inquiry and how science has traditionally excluded groups from its practices.

How Is Scientific Knowledge Generated

Science aims at descriptions, explanations, and predictions of natural objects and phenomena, primarily by means of observing and theorising. We have seen in

TABLE 2.1 Brief Description of the Elements of Scientific Knowledge

Element of scientific knowledge	*What it characterises*	*Few examples*
Fact	An observation that has been confirmed repeatedly and for all practical purposes accepted as ‘true’ is taken to be a fact. The ‘truth’ in facts is fallible, i.e., potentially open to change.	Air has weight and occupies space. The earth moves around the sun. Living things need food to survive.
Concept	A concept is a generalised idea of an object/substance or its properties. The concept of an object can relate to a specific example or a general set of shared features. Property concepts are more complex and describe a set of concepts or make associations among different concepts. A concept is primarily a mental representation and abstract proposition which helps organise sets of ideas and facts.	Carbon. Atom. Element. Energy. Heredity.
Principles	A scientific principle like a scientific law describes a relationship between two quantities. The difference between law and principle is in the nature of the relationship. The relationship described by a principle is subject to changes if the conditions of the quantities that are related change.	Archimedes’s principle describes the relationship between buoyant forces and fluids but the exact nature of that relationship depends on the particular fluid, the properties of the object in the fluid, the pressure exerted upon the fluid and so on.

Laws	A scientific law describes a generalisation about some phenomena of nature (Feynman, 1965). Most laws can be represented as an equation (which is a mathematical formula). The formula can be used to predict an outcome. Specifically, once applied, the formula predicts that a new observation will conform to the law. A valid scientific law can accurately predict natural phenomena. However, like other scientific knowledge and unlike mathematical knowledge, scientific laws do not have absolute certainty. It is always possible for a law to be overturned by future observations.	Newton's law of gravitational force. The periodic law of elements. Mendel's laws on genetics.
Theories	A scientific theory is a comprehensive explanation of some aspect of nature and is supported by a vast body of evidence that has been repeatedly confirmed through observation and experiment. Unlike the popular assumption that a theory becomes a law with additional evidence, the two serve different purposes for understanding the natural world. Many scientific theories are very well established and they are seldom, if ever, entirely replaced but are refined, based on new evidence.	Atomic theory of matter. Heliocentric centric theory. Gene theory.

Source: Compiled by the author.

the previous section, observations are framed by theoretical frameworks and help the observer make sense of what is observed. Philosophers of science consider this integration as necessary (Boyd & Bogen, 2021).

Descriptions in science are systematic. Scientists tend to use generalised descriptions and the level of abstractions varies in different fields of science. Scientific descriptions mostly take the form of classification, taxonomy, nomenclature, periodisation and quantification (Hoyningen-Huene, 2013). The use of mathematical concepts for scientific description can be traced to Galileo. As Sarukkai enumerates, the description of a falling body can take numerous forms but Galileo focussed only on the height from which it falls and the time taken to fall to describe the falling body, both of which are quantifiable (Sarukkai, 2012: 37).

Explanations are given by way of answering specific why-questions. Scientific explanations use empirical generalisations and theories. An example of empirical generalisation is Galileo's explanation of a freely falling body in terms of the inverse relationship between height and time, while Newton's gravitational theory offers a comprehensive explanation for a range of phenomena, including the free fall of objects on earth's surface (Hoyningen-Huene, 2013). Scientists use theoretical terms to account for unobservable entities in a phenomenon they are explaining (Appiah, 2003). There are numerous examples of such theoretical terms, including tangible objects such as atoms which were not observable at the time of their discovery and the intangible such as gravitational force. Just as descriptions can never recreate an object or phenomena exactly, explanations can never be absolutely complete (Thagard, 1992).

Prediction refers to the future, objects and phenomena that have not been observed. Scientists in some fields are able to make predictions due to the regularity of the natural phenomena they study. Predictions that are also based on correlations with other data sets, based on theories or laws and models (Hoyningen-Huene, 2013). There are innumerable examples of predictions made by scientists that have been later proven by experimentation or observation. Mendeleev's example of predicting properties of hitherto unknown elements from his periodic table is described in the first section.

What Is Scientific Inquiry?

ACTIVITY 2.4 BLACK BOX ACTIVITY

This is a popular activity among educators!

There are many variations to the black box. A simple version has an assortment of objects put together inside a sealed, opaque box with a small hole. The objective is to conjecture the objects inside through your senses (sound, touch) and tools such as a magnet or torchlight. This activity models how some scientists study objects and phenomena that cannot be directly observed such as the interior of the earth, galaxies light years away or understanding the transmission mechanism of the COVID-19 virus.

Your faculty or one of your classmates can assemble the black box.

Scientists differ greatly in what they inquire and how they plan their investigations. Depending on what they are inquiring into, investigations can be descriptive (generally involves describing and/or quantifying parts of a natural system); comparative (example: collecting data on different populations/organisms, under different conditions such as different times of the year or in different locations to make a comparison); and experimental (designed in such a way that known variables are identified and some of the variables are actively manipulated, controlled and measured in an effort to establish a causal relationship). As you would have experienced in the black box activity, scientists often have to rely on their observations and inferences to develop experiments to test their theories about objects and phenomena that they cannot directly see.

Most scientific investigations broadly rely on these processes. It is important to remember that these processes are interconnected and not sequential.

- Observing and questioning: Prior observations are the basis for questions about a phenomenon or an object that we want to inquire into.
- Forming a testable hypothesis: A testable hypothesis provides a tentative explanation based on the initial observations. An important aspect of this ability is to refine and focus the questions on objects/phenomena in a way that they can be described, explained or predicted by scientific investigations.
- Designing and conducting a scientific investigation: This will involve systematic observation, making accurate measurements and identifying and controlling variables. The investigation is primarily guided by the question framed and is a means of testing the hypotheses.
- Using appropriate tools and techniques to gather, analyse and interpret data: These will again be guided by the hypotheses and the investigation designed.
- Developing robust descriptions, explanations, predictions and models using evidence: Evidence is crucial to science. The validity of scientific knowledge is established by the ability to think critically and imaginatively to establish logical relationships between evidence and explanations.
- Communicating procedures for investigation, gathering evidence and arriving at explanations: Science demands accurate record-keeping, openness and replication. Scientists evaluate each other's results of investigations and explanations through a review process.

While explanations in science are empirical, i.e., based on observations of the natural world, it involves human imagination and creativity. Science is not a lifeless, orderly activity as imagined by many and involves inference, speculation, conjecture and invention of explanations which requires creativity. Ultimately the acceptance of explanations as plausible is based on verification principles that the community of scientists find credible. Scientific inquiry is therefore a complex cognitive activity derived from human efforts that systematically gathers and interprets observations to generate knowledge about the natural world through collaboration, discussion and debate.

Inquiry in the Science Classroom

A primary aim of science education is to initiate students into scientific inquiry as they develop an understanding of science as a way of knowing and explaining the natural world (NCERT, 2006). Their classroom experiences must help students develop cognitive abilities and competencies associated with scientific inquiry (Bybee, 2006). In case of inquiries in a science classroom, Ramadas et al. (1996) suggest that one of the simple ways to introduce scientific inquiry even at the elementary school level is to produce a phenomenon and initiate discussions.

BOX 2.4 REFLECTION ON INQUIRY

Here is an example to help reflect on what inquiry in a school can look like. As you read the excerpt, reflect on aspects of classroom inquiry that are similar to the processes of scientific investigation described earlier and which ones are unique to a classroom context.

> During her class 6 students' investigation of the interaction of light and matter, Ms Susan began with the KWL (what do I know, what do I want to learn, what have I learnt) to initiate students' engagement with light and shadows. Based on their responses, she introduced this question: How does light interact with solid objects? She began the explore phase by ascertaining students' understanding of the question. A boy asked, 'What is a solid?' Students responded with statements such as: 'A solid is not like water'. 'It's filled in'. 'It's hard'. 'It doesn't bend'. At this point, Ms Susan picked up a bendable solid, bent it and asked the students whether it was a solid. Students were not sure. Ms Susan proceeded to review states of matter with the students, discussing properties and examples. She then returned to the preparation for investigating light.
>
> The students wanted to test with more than 20 materials (blue plastic sheet, colourless plastic sheet, plastic sheet with gold coating on one side and so on). They planned to shine torchlight through these materials. Ms

Susan then introduced a new tool to the students: a small rectangular piece of white paper, which she called a 'light catcher'. This tool functioned as a screen to look for reflected or transmitted light.

In addition, the class talked about categorizing objects in terms of how light behaved. Ms Susan asked the students what they thought the light might do, and they discussed categorising the objects based on whether light bounced off, went through, became trapped, or did something else (the students were not sure what this might be, but they wanted to have a category for other possibilities). In the course of that conversation, Ms Susan introduced the terms 'reflected', 'transmitted' and 'absorbed', which she stated were terms used by scientists to name the behaviours they had described.

Adapted from Donovan and Bransford (2005: 438, 445).

Exclusionary Practices of Science

Historically, women and persons of colour have been excluded from science. Male domination and association of characteristics of objectivity, rationality and brilliance tend to be biased towards white men. Also, access to peer networks enjoyed by white, affluent, male students provides them with information on expectations and opportunities not available to less privileged students (Leslie et al., 2015). Science is also highly competitive right from entrance examinations to college admission to awarding financial grants and other awards (Sarukkai, 2012). This coupled with a widespread belief in science promoting meritocracy has also meant the continued exclusion of many sections of the society. Feminists have long argued that knowledge results from social interactions among members of a community and not due to some objective, disinterested logical considerations (Harding, 1996). These aspects are discussed in more detail in the chapter on inclusive education.

BOX 2.5 REPORT ON HOW YOUTH FROM RURAL AREAS AND TRADITIONALLY MARGINALISED CASTES MISS OUT ON HIGHER EDUCATION AND PURSUING SCIENCE IN INDIA

Here is a report on how youth from rural areas and traditionally marginalised castes miss out on higher education and pursuing science in India.

Vast numbers of talented students in India never get to realize their full potential owing to poor rural schools, language barriers and the caste system. Especially outside the cities, higher education – including science – largely remains a privilege of the rich, the politically powerful and the upper castes. India's national census does not collect data on caste, rural or gender representation in science, nor do the country's science departments. Nonetheless, says Gautam Desiraju, a chemist at the Indian Institute of Science in Bangalore, it is clear that rural Indian students are hampered by a lack of good science teachers and lab facilities, and are unaware of opportunities to enter mainstream science (see www.nature. com/ indiascience). The barriers are even higher for rural girls, who are discouraged from pursuing higher studies or jobs, and for girls from poor urban families, who are expected to take jobs to contribute to their dowries. Many rural students are also hampered by their poor English, the language that schools often use to explain science. 'Teachers from elite colleges and interview and selection committees are often biased against such students', says immunologist Indira Nath, at the Indian National Science Academy in New Delhi. Caste is officially not an issue. India's constitution and courts have mandated that up to half of the places in education and employment must be reserved for people from historically discriminated-against classes. However, a clause excludes several of India's top science centres from this requirement. And in reality there is an 'unintentional, subtle or hidden discrimination against students from reserved categories, right from high school to college levels', says Shri Krishna Joshi, a scientist emeritus at the National Physical Laboratory in New Delhi. Teachers do not encourage them as much as they do students from upper castes. As a result, he says, 'poor students from reserved categories in turn often have psychological barriers and believe they cannot compete with the others'.

Source: Padma (2016)

Further Readings

In the second chapter titled 'Doing Science', Sarukkai explains what theory building and experimentation mean in science.

Sarukkai, S. (2012). Doing science. In *What is science?* National Book Trust. Chapter 2.

The chapter by Bybee provides a detailed explanation of scientific inquiry and science teaching and how teachers can organise inquiry in classrooms.

Bybee, R.W. (2006). Scientific inquiry and science teaching. In L.B. Flick & N.G. Lederman (Eds.), *Scientific inquiry and nature of science*. Springer.

Scientific Enterprise

ACTIVITY 2.5

Draw a picture of a scientist at work.

Compare it with pictures drawn by your classmates and discuss the predominant image that emerges.

In one of the earliest studies in India on students' idea of science and scientists, drawings of students of grades 6 to 8 revealed more than three-quarters of students surveyed depict a scientist as a young/middle-aged male (Chunawala & Ladage, 1998). Is that the case with your drawings as well? What does it communicate about the scientific enterprise? Reflect on implications for a socially just science education.

Repeat the activity with school students of any grade and analyse their drawings for students' current conceptions of scientists.

Institutionalisation of Science

People tend to think of science as something done by scientists in a laboratory. But science happens in different settings. Historically, many scientists were self-employed and pursued it as a hobby. Some were funded by religious institutions and royalty. In the present times, the scientific enterprise is increasingly institutionalised. Most scientists are employed in research organisations, industries, hospitals, universities, scientific associations, government departments and so on. They may work individually, in small groups or as members of large research teams. Science as an enterprise therefore includes individuals, society and institutions.

BOX 2.6 LARGE-SCALE SCIENCE

Current research in science is mostly undertaken by teams, sometimes in very large numbers. For example, CERN is a European nuclear research project involving very large teams working on different aspects. In 2013, the laboratory is supposed to have had 2,513 staff members and hosted some 12,313 scientists and engineers representing 608 universities from 113 countries.

Source: http://home.cern/about/who-we-are/our-history

Science as a Human Endeavour

Science may be a complex social activity conducted in various institutions, funded by the governments, the corporate sector or private foundations, but the vast body of scientific knowledge has evolved through human endeavour.

- Scientific ideas do not automatically emerge from data or get stumbled upon by their discoverer like a new continent or animal.
- Scientific knowledge is created by people using common human qualities like reasoning, insight, imagination, skill, hard work and creativity and also dispositions such as intellectual honesty, scepticism and openness to new ideas.

- Men and women from different cultures, with different interests, talents and motivations, have contributed to the development of science.

Biographies of scientists and the development of concepts and theories offer a fascinating glimpse into the scientific enterprise. Also, scientists present the human side of this enterprise. Episodes from the history of science are also known to be a very effective pedagogic tool to convey nature of science, foster understanding of concepts and sustain students' interest in science.

BOX 2.7 BRIEF SKETCH OF THREE SCIENTISTS FROM DIFFERENT TIMES AND COUNTRIES

A brief sketch of three scientists from different times and countries with different backgrounds, and an incident involving two scientists in an Indian science institute are given here. As you read, look for commonalities and differences among the scientists. Reflect on the ingenuity of the human mind on the one hand and the extraneous factors that influence scientific enterprise on the other. What do these examples communicate about the scientific enterprise? Collect more such narratives for your own use as a teacher. Including such narratives will not only make your science class interesting but more crucially they can be used to communicate nature of science to students.

Ibn al-Haytham (965–1021)

Ibn al-Haytham was born in Basra (present-day Iraq) and was educated there and in Baghdad. During his time in Iraq, he worked as a civil servant and read many scientific books. Ibn al-Haytham proved that rays of light travel in straight lines, and carried out a number of experiments with lenses, mirrors, to study refraction and reflection.

He was summoned to Egypt by the caliph al-Hakim to regulate the flooding of the Nile. After his fieldwork made him aware of the impracticality of this scheme, and fearing the caliph's anger, he feigned madness. He was kept under house arrest from 1011 until al-Hakim's death. During this time, he wrote his influential *Book of Optics* which has been ranked alongside Isaac Newton's *Philosophiae Naturalis* and *Principia Mathematica* as one of the most influential books in the history of physics.

George Washington Carver (1864–1943)

George Washington Carver researched agricultural practices and products. The products he derived from peanut and soybean revolutionised the economy of the southern USA which was till then excessively dependent on cotton.

Carver was born a slave in the USA. While working as a labourer in cotton fields, Carver managed to obtain a high school education under extremely difficult circumstances. He was the first black student to be admitted to a college. While working as the school cleaner, he received a degree in agricultural science at the age of 30 and received a master's degree from the same university two years later. Carver became the first African-American to serve on its faculty. Within a short time, his fame as an agricultural scientist spread. Carver never patented his discoveries, saying, 'God gave them to me, how can I sell them to someone else?' He donated his life's savings so his work might be carried on after his death.

Lise Meitner (1878–1968)

Lise Meitner, an Austrian, was barred from higher education when she was 14. She had heard about Röntgen and Becquerel's discoveries of radioactivity and was determined to pursue her studies. Lise wrote to Marie Curie who was then working in France. But, Curie could not accommodate Lise in her lab. But that did not deter Lise and she went to Germany to work with Otto Hahn to study radioactive elements. The university did not allow a woman to work in its laboratory, so Lise worked in the basement. During the Nazi rule, she fled to Sweden but continued to collaborate with Otto Hahn, long distance. Although she extended Hahn's discovery of splitting of uranium atoms and named the phenomenon 'nuclear fission' only Hahn was given the Nobel Prize.

C.V. Raman's Attempt to Create a Position for Max Born at IISc, Bengaluru

When C.V. Raman became Director of the Indian Institute of Science (IISc) 24 years after it was founded, it still had only four departments. He established a physics department soon after taking up the post and as its only faculty member set up research projects along with his students in areas relating to both theoretical and experimental physics, leading to several publications of high quality in a short period of time. But he wanted to make it a world-class centre for physics and wanted to attract physicists of the highest calibre. This was the period of the rise of the Nazis in Germany. Jewish physicists were being forced out of their country and Raman tried to convince some of them to come to IISc. Max Born accepted his invitation. Born was an internationally reputed physicist and later a Nobel laureate, and was a pioneer in quantum physics at that time. But when Raman tried to make Born's appointment at the institute permanent, institutional politics did not allow him to do so. According to Born, opposition to Raman began when he attempted to speed things up at the 'sleepy place where little work was done by a number of well-paid people' at the institute. Born describes the Senate meeting where an English professor who was recently appointed to the institute attacked both Raman and Born. Born writes:

> The English Professor Aston went up and spoke in a most unpleasant way against Raman's motion, declaring that a second-rank foreigner driven out from his own country was not good enough for them. This was particularly disappointing since we had been kind to the Astons, as I mentioned before [they stayed as guests with the Borns when they arrived until their bungalow was ready]. I was so shaken that when I returned to Hedi [Born's wife], I simply cried.
>
> (quoted in Ramaswamy, 2019)

Source: Compiled by the author from the American Chemical Society (https://www.acs.org/content/acs/en/education/whatischemistry/landmarks/carver.html); the World of Ibn Al-Haytham (https://www.ibnalhaytham.com/); the Atomic Heritage Foundation (https://www.atomicheritage.org/profile/lise-meitner) and Connect (https://connect.iisc.ac.in/2019/12/when-raman-brought-born-to-bangalore/).

It is widely acknowledged that scientists contribute to the advancement of scientific knowledge through their inquiries. However, science teachers play a critical role in the scientific enterprise as well, by initiating students into the ways of thinking and practices of the scientific endeavour (NCERT, 2013).

Scientific World View

A world view is a system of beliefs, perceptions or philosophy of life and reality. Individuals, families, communities and countries can have distinct worldviews. Over the centuries, scientists have come to share certain beliefs and perceptions about the natural world and how to study it.

- Starting with Galileo, scientists believe that the universe is understandable. Scientists also assume that the universe is uniform in which the basic rules are everywhere the same. This uniformity allows knowledge gained by studying one part of the universe to be applied to other parts (Merton, 1973).

  There are many examples in the history of science that depict this world view. A classic example is Newton's discovery that the same principles of motion and gravitation that explain the motion of a falling object on the surface of the earth, also explain how the moon and the planets move. This discovery discarded the idea that the heavens and heavenly bodies were different and showed that they obeyed the same natural laws as those of earth.

- Galileo famously described nature as 'an open book' that can be understood through careful, systematic study. He also believed that nature has a special language that best describes it. This special language happens to be mathematics (Sarukkai, 2012).
- Scientists, in principle, view all scientific ideas as tentative and subject to change and improvement.

Values Associated with Science

There is a common perception that science is value-free and that scientific facts are objective. However, science is not just a body of knowledge nor only a means of accumulating that knowledge. It is a social activity that reflects certain values and ethics under which scientists generally work. The values such as encouraging scepticism and questioning authority, fostering curiosity, rewarding creativity and imagination, promoting cooperation, being persistent, maintaining honesty and integrity are ascribed to scientists. Some of it is due to the practices that have evolved among scientists as a community where data sharing for open scrutiny and rigour in reporting are valued. So both the processes and what is accepted as knowledge in science is scrutinised by experts in the concerned domain. Being open-minded, having a willingness to suspend judgement, respect for life, appreciation for aesthetics and simplicity of ideas are generally highly valued in science. However, as we have seen earlier, science is a human endeavour and reflects societal biases and prejudices, as well. While there are many examples to illustrate these values and ethics, the history of science also provides many counterexamples. Nevertheless, science has progressed because as an enterprise, by and large science tends to reward those who adhere to these values and ethics. Also, these values are certainly not unique to science, but representative of other human endeavours as well.

Science has doubtless taught us to rethink existing social values and ethics at different points of time in history. But it is also a fact that in solving some problems, science has introduced new problems about values they cannot solve. Scientists tend to excuse themselves from addressing moral dilemmas, saying 'pure' and 'applied' research is different. But this is unacceptable. As a member of society, the researcher, even if 'doing' pure science, becomes an ethical agent responsible for the consequences of his or her actions. It is important to remember that moral dilemmas cannot be resolved by science alone, nor can scientists disregard them as irrelevant. As the science philosopher Allchin (1988) points out, it is time we adhere to conventional values about prudence and respect for life in reshaping current values about waste, consumption, modes of production and our relationship to nature. This comes with a better understanding of nature of science and the relationship between science and technology.

ACTIVITY 2.6

What does this extract tell you about the values that Prof. Feynman finds important?

> Scientists need a specific, extra type of integrity that includes not lying, but also bending over backwards to show how you may be wrong. And this is our responsibility as scientists, certainly to other scientists, and I think to laymen. For example, I was a little surprised when I was talking to a friend who was going (to give a talk) on the radio. He does work on cosmology and astronomy, and he wondered how he would explain what the applications of this work were. 'Well,' I said, 'there aren't any.' He said, 'Yes, but then we won't get support for more research of this kind.' I think that's kind of dishonest. If you're representing yourself as a scientist, then you should explain to the layman what you're doing – and if they don't want to support you under those circumstances, then that's their decision.
>
> (Feynman, 1992: 343)

Do you think all scientists adhere to this value? Substantiate your response with an example.

Science and Technology

Technology is generally considered an application of science. However, the relationship between science and technology is more complex. Scientists use different technological artefacts for measuring, experimenting and observing. For example, Galileo furthered the understanding of astronomy when he put into use the telescope first built by Hans Lippershey who was a manufacturer of eyeglasses. Technological artefacts in turn inspire the development of a new scientific explanation. An example of this is the steam engine built by Sadi Carnot, and Lord Kelvin developed thermodynamics to provide a scientific explanation of the processes that occur inside a steam engine (Cuevas, 2005).

Both science and technology have been very successful human enterprises. Science and technology have always been an intrinsic part of every society, both shaping and being shaped by the society. They have been powerful forces of change.

> The changes may relate to survival needs such as food, shelter or defence, or they may relate to human aspirations such as knowledge, art or control. But the results of changing the world are complicated and unpredictable. They can include unexpected benefits, unexpected costs and unexpected risks – any of which may fall on different social groups at different times.
>
> *(AAAS, 1998: 39)*

The COVID-19 pandemic has very vividly brought this out.

As with any human enterprise, science is also fraught with many issues. It is important for a science teacher to be critically aware of the problematic nature of the scientific enterprise. However, science offers a powerful and distinctive way of understanding the world around us. Scientific knowledge has helped raise human society from obscurantism and blind practices and opened up many vistas of understanding. While it is the case that science and its products have brought in their wake both enormous benefits and destructive capabilities, there is no question that they are constantly changing the way we live.

> **ACTIVITY 2.7**
>
> Imagine there is a student in your class who is not interested in learning science no matter what you do. When questioned, he says scientists have ruined the world and he does not want to learn anything to do with science. What measures will you take to ensure the student alters his one-sided view of science?

Further Readings

Sundar Sarukkai discusses multicultural contributions to science and issues related to ethics and science in Chapter 6. In the last chapter of the book, he enumerates what has contributed to the successes of science and takes stock of its limitations.

Sarukkai, S. (2012). Science and the human subject. In *What is science?* National Book Trust. Chapter 6.

Sarukkai, S. (2012). Success and limitations of science. In *What is science*? National Book Trust. Chapter 7.

Education for Nature of Science

In the present world, everyone needs to be scientifically literate, of which nature of science forms a component. The National Focus Group on Science Education in India had noted 15 years back:

> In a democratic political framework, the possible aberrations and misuse of science can be checked by the people themselves. Science, tempered with wisdom, is the surest and the only way to human welfare. This conviction provides the basic rationale for science education.
>
> *(NCERT, 2006: 2)*

In this section, we will discuss why an understanding of nature of science is important, what some of the tenets of nature of science are and how teachers can include nature of science in their classroom teaching. We avoid using 'the' nature of science to indicate there is no one nature of science.

Why Study Nature of Science?

Science impacts virtually every aspect of modern life. But literature shows that the general public has only a basic understanding of the scientific endeavour. This lack of understanding is potentially harmful, particularly in democratic societies because it can influence funding decisions, evaluation of policy matters, making sense of evidence and ethical considerations of the inventions of science (Driver et al., 1996). One reason for this lack of understanding is the way science is taught across levels emphasising learning of science content without either an engagement with the processes of knowledge generation (as described in the preceding sections) or with the everyday contexts. Nature of science would help science teachers portray the scientific endeavour better to students (McComas, 2002). Science teachers should therefore engage with an understanding of the knowledge generation processes and translate them into meaningful classroom experiences and appropriate classroom discourse. Driver et al. (1996) also point out that an understanding of nature of science 'supports successful learning of science content' (20).

ACTIVITY 2.8 REFLECT

During an interaction with 20 BEd students of one institution, these were the ideas on nature of science that student teachers came up with:

- Careful observation is important in science.
- We infer from our observations based on our previous knowledge.
- Verification is important for science to accept a statement as truth.
- There are systematic processes, which scientists follow to arrive at conclusions.
- The process is replicable. Science also relies on inference and interpretation because all the phenomena are not directly observable.

Which of these ideas are problematic for a teacher? Why? How can they be addressed?

Tenets of Nature of Science

Nature of science describes what science is, how it works, how scientists function as a social group and how society and science are intertwined. Nature of science draws from diverse fields such as history of science, sociological studies of science, philosophy of science, cultural studies and psychology. There is considerable debate among scholars on what constitutes nature of science. However, there is a broad consensus among science educators and philosophers of science that science is an empirical human endeavour and scientific knowledge is tentative, subjective, socially and culturally embedded and not value-neutral (McComas, 2002; NCERT, 2006; Flick & Lederman, 2006).

Tenets of nature of science include (Eflin et al., 1999):

- Curiosity spurs scientists to acquire knowledge of the physical world.
- There is an underlying order in the world that science seeks to describe in a simple and comprehensive manner.
- Science is dynamic, changing and tentative.
- There is no one, single scientific method.

Science curricula have long been criticised for not incorporating aspects of nature of science such as role of theory, explanations or models. Also, pedagogic practices in science classrooms have largely remained devoid of active involvement of students and provide little incentive to ignite their curiosity (NCERT, 2006). As a result, students rarely experience what it means to 'do' science or how knowledge in science is generated.

ACTIVITY 2.9

Science has given us unique concepts to describe the world. Some like 'lines of force' and 'genes' are theoretical. Define four such theoretical concepts and design a plan to teach them to secondary school students.

Integrating NoS in Science Classrooms

Science educators agree that nature of science has to be integrated with science content and process in classrooms. It cannot be taught in isolation. A number of ideas for activities to integrate nature of science in classroom teaching across grade levels are available. Some of the pedagogic practices include the use of historical examples of inventions and discoveries and tracing the path of discovery of an object or phenomenon (a historical approach to teaching science is elaborated in Chapter 5).

The story of William Beaumont's investigations into the process of digestion illustrates the tentative nature of scientific knowledge, the important role of experimentation in developing that knowledge, and also serves as an example for raising issues of ethics in science. Beaumont, a medical practitioner, saved the life of 'Alexis' who was severely injured in an accident but a 'hole' was left open on the stomach of Alexis because he refused to get it operated upon. Beaumont saw it as an opportunity to observe what happened in the stomach when it received food. He also experimented with Alexis's stomach by placing food in there, collecting the gastric juice to analyse later and so on. In those days, some people had believed that digestion is a mechanical process brought about by the grinding action of muscles. Beaumont, on the basis of his controversial experiments, enhanced our understanding that digestion in the stomach was a chemical process (Hrala, 2016). Stories about science and scientists provide a rich source of science as human enterprise and the way scientific knowledge develops. The story of Rosalind Franklin, for instance, shows how there is no one method of reaching breakthroughs in scientific knowledge generation, and how societal factors such as gender influence scientific practice. Watson and Crick together and Franklin were all interested in elucidating the structure of DNA. While the former took the model-building approach, Franklin preferred to investigate the molecular structure using X-ray diffraction techniques. The former duo could not have developed their model of the structure of DNA if they did not possess the data that Franklin had generated. Yet, her role was not recognised by Watson and Crick, nor by the committee that decided upon the Nobel Prize.

Open-ended laboratory activities provide an opportunity to model the tenets of nature of science. Engaging students in investigations of common freshwater animals such as hydra enable students to experience different stages of a scientific inquiry themselves. For example, questions such as what do hydra eat, how can hydra be maintained in a lab and where in our immediate environment can we find hydra are some open-ended questions which allow students to engage in hypothesis formation, designing experiments, documenting and presenting data and observations – thus modelling the scientific inquiry in a real-world setting.

The project-based approach to teaching science, discussed in the previous chapter, also helps develop the nature of science. During the COVID-19 pandemic, vaccination and masking are two ways to help prevent infections. Despite this, a large number of people have expressed apprehensions about vaccines and have refused to take them. In this context, students can work on a project to understand people's concerns about available vaccines, and ways of explaining to them, in simple terms, how vaccines work so that more and more people take them. Since the issue can be of personal significance to each individual, students would have to be sensitive about how they handle their interactions. While they are explaining the workings, nature and limitations of vaccines they would learn about how scientific knowledge gets generated and verified, they will get opportunities to make distinctions between science and pseudoscience, and they will get to experience science's interaction with society in real time.

ACTIVITY 2.10

At the beginning of the chapter, you were asked to describe what you think science is. Which of these four categories of views described by Cobern and Loving (2002) do the views of your class represent:

1. Scientism: Science is the best way of knowing and is the perfect discipline.
2. Anti-science view: Science is overrated. One should not attach much value to the aims, methods or results of science.
3. Cultural view: Science is embedded in a social, historical and psychological context which affects all that goes on in science.
4. Balanced view: This viewpoint, which reflects our own aversion to extremism, takes science to be a complicated affair that cannot easily be reduced to one or even a few simple descriptions.

How did your views alter as you engaged with this chapter? Did you become more appreciative of the complex nature of science?

Reflect on the problems that can arise from a science teacher holding onto a one-sided extreme view such as scientism or anti-science.

Further Readings

This book discusses why teaching nature of science is important and has a number of ideas for classroom teachers:

McComas, W. (Ed.). (2002). *The Nature of Science in Science Education; Rationales and Strategies*. Kluwer Academic Publishers, New York.

This collection of case histories by James B. Conant is a classic text to help undergraduate students and others understand the nature of science: https://archive.org/details/harvardcasehisto010924mbp/page/n145/mode/2up.

SUMMARY

In this chapter, we have taken a brief look at nature of science, which draws from many different disciplines including philosophy, sociology and psychology. Modern science as a body of knowledge has evolved over five centuries. At present science represents a very wide range of ideas about the physical, biological, psychological and social worlds. These ideas are interconnected and interrelated. They have been validated through particular ways of observing, thinking and experimenting. These ways constitute nature of science and reflect how science is different from other bodies of knowledge.

- Elements of scientific knowledge

Among other aspects, it includes the content of science that has evolved into a vast domain of knowledge, considered under the umbrella of scientific enterprise; the processes through which this knowledge was constructed which include scientific inquiry; and particular ways of looking at the world in the process of evolving this scientific domain of knowledge, called scientific world view.

- Values associated with science

Values are both inherent to science, in the sense that they are generally valued by most scientists and ascribed to science, that is society attributes them to science. However, science being a social enterprise and scientists being as human as the rest of us, there are both positive and negative instances of adhering to these values.

- Science and technology

Science and technology have a huge impact on society, some of which is tangible, which we can easily perceive. But neither the tangible nor intangible impact of science and technology on society can be considered entirely beneficial or harmful. The interface among science, technology and society is complex and multilayered.

Exercise and Practice Questions

1. Look at the image given and describe what you see. Compare your description with the rest of the class. Discuss how much of what all of you have described is based on observation and how much on inference (Figure 2.1).
   (Adapted from McComas, 2002)
2. Critically evaluate nature of science perspectives in a science textbook. You can use some of these as criteria for your evaluation:
   - if science is presented as a process or a product.
   - if aspects of nature of science are articulated or left for the reader to infer.
   - whether there is an emphasis on facts and information and inadequate engagement with concepts and theories.
   - if there is distortion/oversimplification of evolution of scientific ideas and discoveries.
3. How will you describe each of the ideas to a grade 6/7 student using an example from history of science or biography of a scientist:
   Experiment
   Theory
   Hypothesis

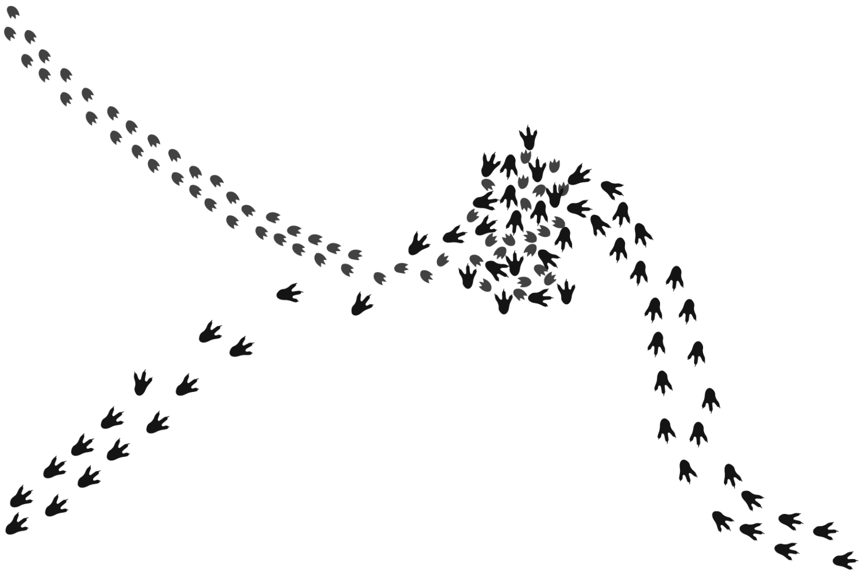

FIGURE 2.1 Observation or inference. Source: Illustration by Ramesh Prakash Khade. Adapted from McComas (2002).

4. Collect a science or technology related article from a newspaper and analyse it in terms of:
   - the nature of the issue.
   - whether different aspects of the issue are portrayed.
   - underlying assumptions.
5. Make a skit out of an anecdote from a scientist's life or an incident from a turning point in the history of science.
6. A study was conducted by Homi Bhabha Centre for Science Education (HBCSE), Mumbai, to ascertain students' views of experiments. It was found that most students think 'experiment' and 'activity' are the same, that is something done with our hands. A majority of them also thought that experiments were done in school by teachers and were related to textbooks. Only 25% of students said experiments were done by scientists. Here are two questions from the study:
   - What is an experiment?
   - Who does experiments and where?

   Each one of you asks these two questions to three to four students.

   Compile all the responses of students collected by all of you and analyse them. What do you think are the reasons for this understanding of experiments among students? What was your own understanding of experiments? Did it change/deepen after you studied this unit?

Note

1 In this book we are considering only natural sciences. When scientific methods were applied to study societies, the disciplines of social sciences evolved. Archaeology, economics, linguistics, political sciences and psychology are some of the examples comprising the social sciences.

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3

A COGNITIVE APPROACH TO LEARNING PHYSICS

আকাশভরা সূর্য-তারা, বিশ্বভরা প্রাণ
তাহারি মাঝখানে আমি পেয়েছি মোর স্থান
বিস্ময়ে তাই জাগে আমার গান

– রবীন্দ্রনাথ ঠাকুর

The sky full of the sun and the stars
The world full of life
Among these I got my place
And in amazement originates my song.
– Rabindranath Tagore

The first two chapters introduced broad ideas in science education and the nature of science. As discussed in the introduction, there are two main approaches to teaching in science education: the cognitive approach and the socio-cultural approach. In this chapter, we will focus on physics education, mainly from the cognitive approach.

OBJECTIVES

The objectives of this chapter are to help you:

- understand physics and its characteristics.
- revisit topics of physics covered in school science.
- summarise important frameworks in physics education research from a cognitive approach.
- reflect on an example of innovative pedagogy based on findings in physics education research.

DOI: 10.4324/9781003047506-4

The chapter is organised as follows:

- Introduction
- Scope of Physics
    - What is Physics?
    - Characteristics of Physics
- Physics Education
    - Physics in School Science Curriculum
    - Research in Physics Education
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- Summary

We use physics all the time in our day-to-day life; while keeping ourselves cool in summer or warm in winter, changing the batteries of a torch (flashlight) or a similar device, deciding the time of day by looking at the sun or the shadows, pulling a chair to sit and so on. Yet, students find the subject of physics difficult and often misunderstand it. The part of the problem with physics is we know it well enough to use it in our daily lives but we often think we know it better than what we actually do. For example, while we correctly decide to use a porcelain cup, rather than a metal cup, for a hot cup of tea, we often think that porcelain is warmer than metal in general. We also think that the sun comes overhead at noon and we know from experience that an object will keep moving only if we keep applying force on it. Now all three are actually incorrect notions in physics. This chapter will introduce many such intuitive notions which students often display. It will also cover why they arise and how they can be addressed.

Before we dive into physics education, we will first briefly discuss what physics is. Then we will learn about some prominent findings in physics education research that will be useful as a teacher. Then we will take an exemplar topic in physics, namely astronomy and see some of the difficulties of students, how they arise and how they can be addressed (Figure 3.1).

FIGURE 3.1 Wondrous universe, inside and out! Source: Illustration by Karen Haydock.

Scope of Physics

What Is Physics?

Physics is perhaps the oldest academic discipline, especially if we include astronomy. The word 'physics' is derived from an ancient Greek word '*phýsis*' which means nature and it simply means 'knowledge of nature'. This is because the word originated when different branches of science were not bifurcated. However, according to its modern usage, inanimate things are studied under 'physical sciences' and a separate branch of life sciences evolved to study living things.

From elementary particles such as electrons and muons to the entire universe, everything is a concern of physics. Roughly, this is a story about how matter (made up of fermions), four fundamental forces in nature (namely, gravitational, electromagnetic, strong and weak forces), space and time interact with each other. The fields of the forces and energy (e.g., waves generated due to disturbances in those fields) also play an important part in the story. And together these things reveal themselves in the most mundane of things such as looking at something, sitting on a chair, walking and talking to the most exotic things such as lightning, shining of the sun and the stars, supernovae and black holes. Ultimately, the interaction between forces and matter will decide the fate of the universe.

We are still far away from understanding how the story of the universe is going to unfold. However, we have made impressive progress in understanding several different phenomena in nature. There are broadly ten branches of physics such as particle (or nuclear) physics, solid-state physics, mechanics (quantum, classical and relativistic), electrodynamics, optics, chemical physics, thermodynamics (which later evolves to statistical mechanics) and astronomy. In addition, there are numerous branches of applied physics such as electronics, thin films, condensed matter physics, biophysics, etc. Each is divided into multiple sub-branches and to gain expertise in any of these sub-branches, researchers spend their lifetimes! Moreover, we are still discovering new things (such as Higgs boson and gravitational waves), our understanding is still evolving (e.g., presence of lunar water was confirmed only in 2009 by NASA's probe which was carried by Chandrayaan-1) and there are still many unresolved things (such as the origin of the moon). As a future teacher, you might wonder, how do we make sure that we know enough about it to teach it to high school students, for such a dynamic and evolving field? Nevertheless, we have seen in the previous chapter that while science is always evolving, there is a strong foundation on which one can build a basic understanding of the world around us.

The vast scope of physics can be overwhelming. Physics can be divided into two parts: classical physics and modern physics. What we teach in high school is a small part of classical physics (which includes laws of motion, work, energy, gravitation, sound, optics, electricity, magnetism, the heliocentric model of the solar system and a little bit of observational astronomy). The only part which falls under the realm of quantum mechanics is Bohr's atomic model, but we teach it for a very valid reason. The structure of the atom forms the basis of modern chemistry, which students must learn to understand a number of phenomena around us. The fundamentals of classical physics are well established. If we know them well, that should be sufficient to teach the subject matter covered during high school.

ACTIVITY 3.1 MAKING PHYSICS PERSONALLY MEANINGFUL

Science in general and physics in particular often deals with abstract concepts and universal principles. Do you think these abstract concepts and universal principles have anything to do with our lives?

What fascinates you about physics? Can learning physics be a source of happiness? Do you remember any moments during your student life when you thought you understood something fundamental or something unexpected? Such moments are called 'aha! moments'. List two or three aha moments around concepts in physics during your student life.

Characteristics of Physics

The central question we ask in science is 'How do things happen and why do they happen the way they do?' Here, of course, there is an assumption that nature is governed by certain laws and can be understood by rational thought, as explained in the second chapter. There is no supernatural power governing it and, at least in principle, what is unknown today can be understood by the human mind in the future. Among the two parts of the question, the answer to the first part, i.e., how things happen, is mostly found out through observations or experimentation. Through observations, we come across patterns such as the annual cycle of seasons. Through experimentation, we may come up with empirical laws such as Newton's law of cooling.

The crucial steps involved in empirical research[1] are to make careful observations, measure or quantify them, note them, look for patterns and generalise them over a number of observations in a range of different situations. A good amount of laboratory experimentation is involved in some branches of physics such as particle physics and solid-state physics whereas other branches such as astronomy exclusively depend on observations.

For the second part of the question, that is, why things happen the way they do, we need to have theories. Theories are based on certain assumptions or models and some of the previously observed facts. The task of a theory is to explain the patterns and laws we observe. They can be extended to come up with predictions which can be tested. In fact, whether the theory proposes predictions which could be tested is one of the important tests of a good theory.[2] For example, the heliocentric model of the solar system can not only explain the seasonal changes but can also predict the transits and occultations of the planets very well.

The crucial step involved in theoretical research is to imagine a model[3] which can explain the observations, make the assumptions in the model explicit, connect the model and the observations through logic or reasoning and predict further observations. In physics, reasoning is almost exclusively carried out with the help of mathematics. In the example of the heliocentric theory mentioned above, a model is necessary but not sufficient to predict transits and occultations. We also need equations which describe the exact motion of the planets which are given by Newton's laws of motion and the law of universal gravitation and further mathematics to make the predictions.

Many times, while verifying the predictions, the observed data does not exactly match the predictions. This prompts some corrections in the theory. Which in turn again gives rise to new predictions. Thus the cycle of theoretical and empirical research continues (an example of this is elaborated through the development of atomic theory in Chapter 4). Furthermore, many times theories can explain data from seemingly different fields. For example, Newton's laws of motion together with the law of universal gravitation explained the varied types of motions on the earth (falling of a ball or projectile motion of a cannonball) as well as motion of celestial bodies (motion of the moon around the earth, motion of planets and comets around the sun, etc.) Similarly, Maxwell's equations unified two seemingly different fields namely electricity and magnetism.

Earlier we saw that applications of physics play a very important role in technological advancement.[4] However, there is an interesting interplay between physics and technology, for technology has played an important role in the advancement of physics. For example, it is the development of semiconductors which gave rise to modern computers, which are extensively used in all branches of research in physics such as research on thin films, which in turn feeds back to the making of different technologies including new-generation electronic devices. Thus we can imagine a fabric of threads of physics and technology woven together.

ACTIVITY 3.2 TEACHING HISTORY OF A TOPIC IN SCHOOL SCIENCE

Take any topic in physics (e.g., heat, light-optics, electricity, magnetism, etc.) and trace its historical development. Write down important steps and mark the empirical (experimental) part in red and the theoretical part in blue. What kind of pattern do you see?

Paying attention to people who contributed, their social class, gender, culture, motivations for carrying out the research, etc. will be useful from the viewpoint of inclusion in the development of science and its implications for science education. This issue is elaborated in Chapter 7.

Further Readings

NCERT (2005). *Physics Part I: Textbook for Class XI*. National Council of Educational Research and Training.

Okasha, S. (2002). *Philosophy of Science: A Very Short Introduction*. Oxford University Press.

Physics Education

Physics education is one of the major themes in science education. Many reforms in physics education have been proposed by educational researchers, scientists and practising teachers. An example of textbooks based upon research would be the *Small Science* curriculum for primary level developed by the Homi Bhabha Centre for Science Education (Mumbai). An example of insightful scientists trying to influence physics education at university level through textbooks would be the *Feynman Lecture on Physics*. *Fundamentals of Physics* by Halliday, Resnick and Walker, and, closer to home, *Concepts of Physics* by Prof. H.C. Verma from IIT Kanpur are examples of textbooks written by eminent physicists and physics teachers for senior secondary schools and undergraduate students. In this chapter, we will limit our scope to school curriculum.

Many Indian states follow an integrated science curriculum till grade 8, and topics in physics constitute a large part of the school science curriculum. In this section, we will first see what is covered in physics at school level and then we will review the research in physics education from a cognitive perspective.

Physics in School Science Curriculum

Formal physics starts around grade 6 when students start to learn concepts such as volume and density. The major branches in physics covered during high school years are mechanics, sound, heat optics, electricity and magnetism (separately during early grades and together at a later stage, as electromagnetism), materials, earth and atmospheric sciences and astronomy. Important concepts covered in

TABLE 3.1 Grade-Wise Syllabus for Two Topics in Physics

Grade	*Mechanics*	*Optics*
6	Measurement of length Rectilinear, circular and periodic motion	Transparent, opaque and translucent object Shadows Image through a pin-hole camera Light travels in a straight line Reflection (plane mirror)
7	Types of motion (straight line, circular, periodic) Measuring distance, time and speed and their units Oscillatory motion (pendulum and its time period) Distance-time graph	Light travels in a straight line Reflection from plane, convex and concave surface Images formed by convex and concave lenses (without refraction) White light is made up of seven colours (without referring to dispersion)
8	Force (magnitude and direction) Effects of force: Change the motion and shape Contact forces (muscular, friction); non-contact forces (magnetic, electrostatic, gravitational) Pressure (F/A) exerted by liquid and gases Atmospheric pressure Friction and its effects Rolling and sliding friction Fluid friction (drag)	Laws of reflection Lateral inversion Regular and diffused reflection Multiple images Working of an eye Dispersion of light
9	Uniform and non-uniform motion (speed and direction) Measurement of speed and acceleration Graphs (distance-time, velocity-time) Equations of motion Uniform circular motion Balanced and unbalanced forces First law of motion (inertia and mass) Second law of motion (momentum and mathematical formulation) Third law of motion Conservation of momentum Law of gravitation Free fall Mass and weight Thrust and pressure (pressure in fluids) Buoyancy, Archimedes's principle, relative density	None

(*Continued*)

TABLE 3.1 (Continued)

Grade	*Mechanics*	*Optics*
	Work done by constant force Power Units and forms of energy: mechanical (kinetic + potential), heat, chemical, electrical, light	
10	None	Laws of reflection Ray diagrams for image formation for reflection from concave and convex mirrors Mirror formula and magnification Refraction from rectangular glass slab Refractive index Ray diagrams for image formation for reflection from concave and convex lenses Lens formula and magnification. Function of the human eye Refraction of light through prism Dispersion Atmospheric refraction (twinkling of stars; advance sunrise, delayed sunset) Scattering of light (Tyndall effect; reddening of the sun at sunrise and sunset)

Source: Author.

two representative topics during high school years according to NCERT (2008) syllabus are given in Table 3.1. (This may vary from state to state but overall the syllabus mostly remains the same.)

ACTIVITY 3.3 PREPARING A TABLE FOR SYLLABUS

Prepare a table of grades vs. important topics for the syllabus you follow. Look for any repetition which could be avoided or any gaps which need to be filled.

Research in Physics Education

There have been sporadic efforts at pedagogic innovations and textbook writing by eminent scientists, insightful teachers and educationists as mentioned earlier. However, systematic research is needed for curriculum and pedagogic reforms and is typically done through studying students' knowledge prior to instruction, students' reception of the instruction (their responses, level of engagement, interest, etc.) and students' knowledge after the instruction. The instructional method under consideration is proposed based on some theoretical frameworks from education (e.g., curricular studies, textbook analysis, pedagogic practices, classroom interactions), psychology (students' interest, understanding, motivation, attitudes, beliefs), sociology (effects of caste, class and gender, and other such marginalisation factors) and researchers typically try to identify why certain methods are effective.

Research in physics education is heavily influenced by research in cognitive psychology. Inquiry-based learning, which later extended as 'guided inquiry', relies on cognitive psychology. An example in the context of physics is in Box 3.1.

BOX 3.1 EXAMPLE OF GUIDED INQUIRY

Topic: Refraction of light
Class: 7
Time: Four periods of 45 minutes duration each
Objective: Help students inquire into the phenomenon of refraction

Session 1 – Introduction

An anecdote from Jules Verne's *The Adventures of Captain Hatteras* was chosen to introduce the students to a discrepant event, namely, 'Making Fire with Ice!' to get them curious.

The following anecdote was narrated to the students.

A few travellers found themselves stranded without fire or anything to light it with. The weather was terribly cold with the temperature at –480 C. 'This is terrible ill-luck. We do not even have a lens to start fire with', said the captain. 'Yes, that's a great pity', the doctor replied, 'because the sun is now strong enough to light paper. Maybe we could …'

'Maybe we could, what?' the captain asked. 'We could try to make fire with ice', the doctor replied.

'With ice?' the captain was incredulous. The doctor chopped off a chunk of ice and carved it with his knife and finally polished it and produced a very good transparent ice block. He focused the sun's rays on the paper using this, and a few minutes later, the paper began to blaze.

Discussions were initiated.

The students were able to infer that this was possible due to the concentration of the sun's rays on paper by the ice lens. The students were then encouraged to ask questions. Most of the questions related to what made the block of ice concentrate the sun's rays to a point.

Sessions 2 and 3 – Verification and Experimentation

To enable students to seek answers to their queries the following activities were demonstrated:

- Objects of different sizes and shapes (pencil, scale, duster, crooked straw, spoon) were immersed in water.
- Objects of different colours (green, yellow and red plastic spoons) were immersed in water.
- Objects were held at different angles in the beaker.
- Objects were immersed in different liquids (castor oil, cooking oil, kerosene, honey, glycerin, saturated sugar solution).
- Objects were immersed in a beaker containing two immiscible liquids (water and castor oil).
- An object (cork) that floats in water was immersed in a beaker containing water.
- An object (a coin) that sinks in water was used.

The students were guided to perform the following activities as well:

- Place a coin in an empty saucer. Step back until the coin is hidden from view. Ask a friend to pour water gradually into the cup. What happens?
- Write something on a piece of paper and place a glass slab over it. What do you see?
- Submerge a mirror in a tub of water. Allow water to settle and observe objects that are outside the tub, through the mirror.
- Make cubes, cuboids and prisms using transparent materials and fill them with water. View any object through them (we had prepared ice of different shapes for this activity).
- Use a magnifying glass and bits of paper. See if you can light a fire with it.

The students were asked to note down their observations and come up with possible explanations through discussions. To facilitate discussion, students were divided into groups of five students each (the class strength was 45).

Session 4 – Formulation of an Explanation

The students were able to relate the bending of objects placed in transparent substances, to arrive at an explanation that the bending of the sun's rays by the ice block focused heat and light into a small spot, thereby causing fire. They were also able to arrive at the following generalisations:

1. The size, colour or shape of the object inserted in the liquid has no bearing on the phenomenon of bending.

2. The objects appear to bend because light bends when moving from one substance to another.
3. The denser the second substance the greater the bending.
4. Only objects that are held slanting undergo bending.

Once the students realised that a magnifying glass causes light rays to bend, they were able to draw a parallel to the use of a lens in microscopes, telescopes, binoculars, eye glasses and divers' goggles.

At the end of the session, the students recalled the sessions and identified the questions that were most fruitful in leading towards the inquiry process.

Source: Author.

QUESTIONS FOR REFLECTION

What combinations of approaches and strategies has the teacher used?
What changes are necessary to make this lesson more inclusive?

How will you transact this lesson differently? You will see another example in the context of teaching chemistry in Chapter 4. An extension of inquiry-based learning is the use of experimentation (which involves inventing new experiments and demonstrations to improve students' learning or encouraging students to design experiments) and observations (Ramadas et al., 1996a). The use of ICT in learning physics is another thriving area in physics education (Osborne & Hennessy, 2003). The socio-cultural approach, as mentioned in the introduction, is the other prominent approach. A pedagogy based on the history of science in the context of teaching biology is given in Chapter 5. In the context of physics education, they are briefly described below in Box 3.2. Researchers have proposed pedagogic methods based on each of these approaches or a combination of approaches. Many of the proposed methods are tested empirically and the extent of their effectiveness has also been documented.

BOX 3.2 SOCIO-CULTURAL APPROACHES IN PHYSICS EDUCATION

As discussed in the second chapter, students should learn about the nature of science along with the content of science. Science is characterised not only by what it studies (which is nature) but also by the kind of questions it asks and the methods and processes it uses to acquire that knowledge. This can be communicated to students through episodes from the history of science. There are several episodes in the history of physics where one can witness the processes involved in scientific enquiry. How experiments lead to empirical laws (e.g., the gas laws), how new insights into theory came through experiments (e.g., Rutherford's gold foil experiment), how theories explain data from multiple fields (e.g., theory of general relativity), how theories are verified or falsified (e.g., Eddington's observations during the solar eclipse) and so on. Moreover, out of three main examples of a paradigm shift in physics (geocentric to heliocentric model, birth of quantum mechanics and theory of general and special relativity), one falls in the scope of high school physics. It is a highly dramatic example that includes Galileo's painstaking observations, ingenious thought experiments and gallantry of challenging the Church. These and such examples can be used to communicate content as well as the nature of science. We will not go deep into this approach since you will see this as a pedagogic approach in the fifth chapter.

Another theme in physics education is inclusivity. Physics often comes across as an endeavour carried out by western (European or American) white men. Physics, among all sciences, has an extremely skewed sex ratio. Hence, physics education has been studied from a 'gender and science'[5] perspective as well (Chunawala et al., 2009). Other aspects of inclusivity such as culture, linguistic background and physical disability are equally important. You will study this in detail in Chapter 7.

Further Readings

Chunawala, S. Vinisha, K. and Patel, A. (2009). Gender, science and schooling: Illustrations in science textbooks and students' and teachers' ideas related to gender. HBCSE, Mumbai.

Ramadas, J., Natarajan, C. Chunawala, S. and Apte, S. (1996a). Role of experiments in school science. DLIPS Report, Part 3. Homi Bhabha Centre for Science Education, Mumbai.

Cognitive Approach to Physics Education

Piaget's work makes the connection between how children construct knowledge and the nature of knowledge. Many psychologists and scientists became interested in how children construct knowledge through informal experiences and planned instructions. The initial research focused on the intuitive concepts children form as a result of the experiences they come across. They are called children's intuitive notions, alternative frameworks and alternative conceptions (also referred to as misconceptions) in different literature. The concepts children form are incorrect according to the agreed-upon understanding of physics, but they are consistent with children's experiences. Moreover, many of these conceptions change as children develop. This leads to a question: How can we facilitate conceptual change through instruction? We will discuss the alternative conceptions and conceptual change in the next subsection. A number of concepts together sometimes form a mental model. Children's mental models and their role in drawing inference will be discussed in the following subsection. This will be followed by a subsection on different types of reasoning involved in physics and how it can be encouraged in physics education. 'Problem solving' being one of the most important skills to be acquired in physics education, we will end this section by documenting important findings regarding 'problem solving'.

Alternative Conceptions

In keeping with the general theme of science education of identifying alternative conceptions in various domains during the late 70s and 80s, early research in physics education focused on alternative conceptions and conceptual change. Some of the prominent researchers who worked in this paradigm were Rosalind Driver, Susan Carey and Lillian McDermott. Many researchers identified alternative conceptions in different topics such as mechanics (force, acceleration, Galilean relativity, Newton's laws), thermodynamics, electromagnetism, optics and astronomy. These alternative conceptions arise because children try to make sense of the world around them and form their own conceptions, frameworks and generalisations. For example, many students think heat is a kind of fluid that flows from hot parts to cold parts, just as fluids flow from a higher level to a lower level.

Another common alternative conception is that force makes things move. Newton's first law states that an object either remains at rest or continues to move at a constant velocity unless acted upon by a force (in an inertial frame), which means an object in uniform motion does not need force to continue its motion. The correct concept is that the force results in changing the velocity of an object (either increasing or decreasing speed or changing the direction of motion). Remember Newton's second law ($F = ma$). This and such alternative conceptions do not change easily even after instruction. This is because students often see in their daily life that they need to apply force to move things and many times even after applying force things do not move. This is because there exists friction between surfaces, another force that arises due to electromagnetic interaction between the molecules on the surfaces of the objects coming in contact with each other. In the lack of this formulation, students often stick to their prior conception. More such alternative conceptions are documented by Driver et al. (1985) and Ramadas et al. (1996b).

Alternative conceptions are formed because children are smart and are actively making sense of their experiences, not because they are incapable of thinking straight. Many of the alternative conceptions are found to be universal, which means they are pretty much the same all over the world irrespective of geographical area and culture.[6] Let us see how alternative conceptions are formed among students in some detail. According to Michelene T.H. Chi (2008), knowledge can be misconceived at three levels: individual beliefs, categories and mental models.

An individual false belief is at the level of a single idea. An alternative conception, such as 'the Pole Star is the brightest star in the sky', is a false belief and can be easily corrected by showing the Pole Star to a child. Some false beliefs are stable, are manifested consistently in students' responses and do not get revised even while learning new information simply because they are not explicitly refuted.

The second level at which alternative conceptions arise is due to category mistake. Concept-based structures are hierarchical in nature (see Figure 3.2 for example), i.e., properties of a concept are shared by all its instances as well as by other concepts in the subcategories which fall under that concept. For example, despite having different colours and melting points, all metals share certain properties such as malleability and electrical conductivity. This property is referred to as 'inheritance', which comes in useful in drawing inferences and providing explanations. For example, once we know that thorium is a metal, we can infer that it will be malleable and will have low electrical resistance despite being very heavy and radioactive.

Since conceptual structures are hierarchical and assume the property of inheritance, it may be imagined as a hierarchical tree structure with branches standing for categories with mutually exclusive properties. When properties of categories are mutually exclusive, they are called categories of a different 'kind' (e.g., metals and non-metals). On the other hand, categories on different branches are 'lateral' categories (e.g., matter and energy). Lateral categories which occur at about the same level within a tree are called 'parallel' (e.g., elements, which falls under matter, and heat, which falls under energy). A physical property of a category can be applied to a member of that category or its subcategories. However, it

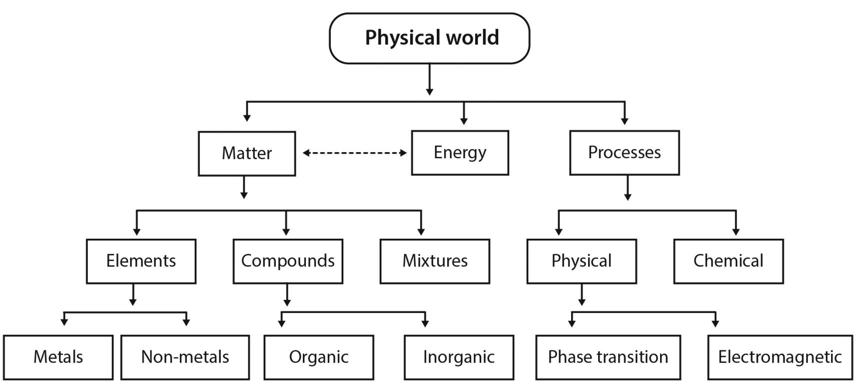

FIGURE 3.2 Conceptual structure is hierarchical in nature. (This is one way of categorising the physical world. Entities can be classified based on their physical state [solid, liquid, gases] or biological state [living, non-living] or in other ways.) Source: Illustration by Ramesh Prakash Khade.

cannot be applied to a member of a lateral category. For example, malleability is a property of material, hence one can measure the malleability of different materials such as gold or carbon. Metals and non-metals being subcategories under material, one can ask questions about the malleability of metals and non-metals. But it is not suitable to ask whether heat is malleable, since heat is not a material.

Ideally, if a learner has no obvious category for a new concept or phenomenon, s/he should assign it to the highest level of category that is appropriate. But instead of assigning it more generally to a higher-level category, s/he may instead assign it to a lateral category, or to a category in a different (ontological) tree altogether. These 'category mistakes' are one of the main sources of robust alternative conceptions. Several examples from physics and other areas are produced in support of this claim by Chi (2008). For example, students often treat concepts such as electric current and light as entities instead of processes. Conceptual change requires a shift across lateral or ontological categories.

The third level at which alternative conceptions arise is the mental model. A mental model is an internal representation of a concept (e.g., the earth), or an interrelated system of concepts (e.g., the solar system) that corresponds in some way to the external structure that it represents. The model can be 'run' mentally, much like an animated simulation, to depict changes and generate predictions and outcomes. An incomplete or non-existing mental model may be so sparse and disconnected that it is not possible to capture its structure. In that case, we can not even say for certain that this mental model is in conflict with the correct scientific model. Children's mental models could be coherent but incorrect, i.e., made up of a number of false individual beliefs. If very few of these beliefs are revised, the complete mental model will not get revised. Also, knowing or learning many correct beliefs does not guarantee the successful transformation of a flawed mental model. Some critical or important beliefs serve to discriminate a flawed model from the correct model.

Chi (2008) notes that a holistic confrontation (using a visual depiction such as a diagram of a flawed mental model and then contrasting it with the diagram of the correct model) may induce successful transformation. We will discuss mental models in more detail in the next subsection and also in our exemplar pedagogy.

Alternative conceptions are an important step in learning. Nonetheless, they are different from accepted frameworks and lead to incorrect inferences in many situations. Therefore a teacher's task is to bring about conceptual change among students. Since alternative conceptions are a product of students' own thinking, they are robust and do not easily change even after instruction. To begin with, we must know where to start. Different students in the class may have different alternative conceptions. We need to identify them in order to design our instruction to facilitate conceptual change for all students.

Conceptual change can happen if the student is dissatisfied with his/her prior conception and an available replacement conception is intelligible, plausible and/or fruitful (Duit & Treagust, 2003). Suppose students hold an alternative conception that force is required to keep an object in motion (the correct notion is, force is required to change the velocity, which includes magnitude and direction, of an object). To make students dissatisfied with their prior conceptions we can present alternative data or ask questions that may help students to reconsider their conceptions. For example, you can ask them why does the cycle keep moving for some distance after you stop paddling (i.e., stop applying force) before coming to halt? You can remind them that people continue to walk in the direction of the bus after getting down from a moving bus.

After such examples, students might be in a position to consider an alternative viewpoint. At this point, the alternative framework you want to provide should be tangible to students. So you would present Newton's first law along with relevant concepts such as inertia and friction. To make it tangible, you may want to evoke students' experiences of friction or give them relevant experiences such as using powder to reduce the friction on a carrom board so that the motion of carrom men can continue with minimal force. Students should also feel that it is plausible. Finally, if students can see that the alternative which you are providing is explaining a number of their experiences, they may find it more fruitful to adopt it and conceptual change may take place. In this case, you can refer to experiences such as getting a jerk when a vehicle stops abruptly, increasing friction by applying the brakes to stop a cycle, etc.

Similar studies with student teachers and in-service teachers have found that they too carry the same alternative conceptions as students. This is another reason why teachers should know the alternative conceptions in different topics: to make sure that they can address their own alternative conceptions and not pass them on to their students. For some topics, diagnostic tests such as 'force concept inventory' and 'astronomy diagnostic test' are available which can be used to identify students' alternative conceptions. For other topics, relevant literature helps teachers prepare their own tests. Sometimes, a teacher can just ask some insightful questions and find something completely unexpected!

As mentioned earlier in this section, alternative conceptions can arise from flawed mental models. In the next section, we will discuss mental models in detail.

Mental Models

Information is arranged in various ways in our minds. A tree-like structure of concepts is one of them.[7] The other prominent structure, where concepts are not arranged in a tree-like structure, is called 'mental models'. Models are at the heart of scientific theories. For example, model of an atom is central to the atomic theory and the heliocentric model of the solar system plays an important role in contemporary astronomy.

Mental models contain various types of information such as visual (colour, brightness) spatial (shape, speed), other physical properties (temperature, electric charge). People usually select a certain part or certain features of the mental model which are relevant to the problem they are solving. For example, we only need to consider valence electrons when we want to explain chemical reactions, the rest of the atomic model (total number of electrons, protons, neutrons, etc.) need not be considered. Typically mental models can be simulated over time to draw inferences.

The term 'mental model' is used in at least two ways. One meaning involves both a mental representation and the process to explain a phenomenon or predict a consequence (e.g., mental models of the day–night cycle). The other meaning is restricted to a mental representation, and when people use it in prediction or to draw inference it is called 'model-based reasoning'. Lehrer and his colleagues have proposed ways for introducing model-based reasoning in mathematics and science at the school level (Lehrer & Schauble, 2000).

Vosniadou and her colleagues extended the research on children's alternative conceptions to research on children's alternative mental models. They documented that children have alternate mental models of the earth such as disc earth, flattened earth (the earth is like a sphere but flattened on the top and we stay on this flat part), hollow earth (earth is spherical but hollow and we stay inside it) and dual earth (the spherical earth mentioned in the textbook is some other planet in the sky). The disc earth is an example of the initial model which children may have formed from their experience of nature and culture, but the other three models (flattened earth, hollow earth, dual earth) are formed when children are introduced to the scientifically accepted model of the spherical earth but an important element of this model, namely gravity, is not discussed. Hence children form a mental model through the synthesis of their own initial model and the scientific model. Therefore, these models are called synthetic models (Vosniadou & Brewer, 1992). Vosniadou and Brewer (1994) also documented students' mental models of the day–night cycle. Samarapungavan et al. (1996) found that Indian students have some additional mental models of the earth closely resembling the model indicated in the indigenous cosmology and inferred that students' mental models are influenced by culture.

Similar research on mental models in physics has been done at various levels such as high school students, undergraduate students, preservice and in-service teachers in topics such as solid friction (Kurnaz & Eksi, 2015; Corpuz & Rebello, 2005); force and velocity (Özcan & Bezen, 2016); heat convection (Sari & Saepuzzaman, 2015); quantisation of light, energy and angular momentum (Didiş et al., 2014) and mechanical system (Hegarty & Just, 1993) basic astronomy (Padalkar & Ramadas, 2008; Subramaniam & Padalkar, 2009; Arslan & Durikan, 2016).

ACTIVITY 3.4 IDENTIFYING MENTAL MODELS IN SCHOOL PHYSICS

Identify three mental models in your physics syllabus. Try to find different ways to teach these models to students.

Model-based reasoning is just one way of reasoning. In the next subsection, we will discuss some other forms of reasoning. The word 'reasoning' is invariably associated with science and scientific thinking. We often use it loosely to indicate 'thinking' or 'giving reason'. Let us take a closer look at the process of reasoning. This will help us to identify places in the curriculum where we can encourage our students to use reasoning.

Reasoning

Reasoning involves the process of producing logically valid arguments. Aristotle proposed four kinds of reasoning in the context of scientific inquiry: inductive reasoning, deductive reasoning, abductive reasoning and analogical reasoning. The first three of these are known as forms of logical reasoning. This section describes these four kinds of reasoning, along with visual-spatial reasoning.

1. *Inductive reasoning*: In its simplest form, it is the process of noticing the commonalities and coming up with generalisations. In the context of the history of physics, all empirical laws (such as Kepler's laws of planetary motion and Ohm's law of electrical resistance) are the result of inductive reasoning. Because of the close connection between empirical data and induction, Piaget calls this kind of reasoning 'empirico-inductive' reasoning and argues that it is present during middle childhood (i.e., concrete operational stage) when children engage in realistic, non-speculative thinking (Flavell et al., 2002). This means students at the upper primary level (grades 6, 7 and 8) are capable of coming up with generalisations based on their experiences and observations. In physics classrooms, they should be encouraged to make systematic observations and come up with rules such as the relationship between the size of the shadow and the distance between the object and a point source of light.
2. *Deductive reasoning*: The process of reasoning from one or more statements (premises) to reach a logically certain conclusion. In the context of physics, one often takes the help of mathematics to carry out deductive reasoning. All derivations (such as deriving the formula for escape velocity or orbital velocity using universal laws of gravitation and Newton's laws of motion) are examples of deductive thinking. This kind of reasoning is more common at the college level and in practice it is often limited to remembering the derivations. More research needs to be done on helping students to construct derivations. Deductive reasoning is also common in problem solving (discussed in subsection 'Problem Solving').
3. *Abductive reasoning*: This kind of reasoning starts with observations and then seeks to find the most likely explanation.[8] In the context of physics, proposing any model or theory to explain data involves abductive reasoning. Copernicus's proposition of a heliocentric model of the solar system to explain the observations of positions of planets or Rutherford's atomic

model to explain his observations of the gold foil experiment are some famous examples of abductive reasoning in the history of physics.

In educational contexts, students need to be encouraged to propose hypotheses to explain their observations. For example, if they observe that gases expand after heating, one can ask them to propose an explanation for this phenomenon. Multiple hypotheses may come in. For example, some students may propose that the molecules of the gases expand in size and some students may propose that the space between the molecules increases (the correct explanation). The pros and cons of such hypotheses can be discussed and students can be asked to come up with predictions which will support their hypothesis. The cyclic process of 'observations – proposing hypothesis or a model – deducing predictions from the model – testing the model – improving the model based on new observation' is known as the 'hypothetico-deductive model'. This is one of the most common descriptions of scientific method.[9] According to Piaget, adolescent students (during the formal operational stage) are capable of reasoning about logical relations irrespective of whether or not premises are true and hence are capable of hypothetico-deductive thinking (Flavell et al., 2002).

4. *Analogical reasoning*: In this process, one identifies similarities between two systems and uses the source system to derive the properties of the target system. Historically, as the name suggests, the 'liquid drop model' of the nucleus used the similarity between a drop of an incompressible liquid and the nucleus of an atom (spherical shape due to surface tension) to derive the semi-empirical mass formula. This model is still widely used to calculate the binding energy of a nucleus and explain phenomena such as radioactivity and fission.

   Analogies can play a powerful role in pedagogic arguments. For example, an analogy between electricity and fluid can be used to explain the concept of current and potential difference (as it was used historically). However, researchers have cautioned that analogies are sources of alternative conceptions too because students can incorrectly extend the features of the source domain to the target domain. For example, when electricity is taught as a fluid students may think that some electricity remains in the circuit even after switching off the power supply just like some water remains in the pipe even after it is removed from the tap. As a teacher, we should be aware of the strengths and limitations of the analogies we use and try to clarify possible alternative conceptions using multiple means.

   Apart from these four traditional ways of reasoning, other ways of reasoning. For example, probabilistic and statistical reasoning have been found important in the context of scientific thinking. However, their potential for science education is so far unexplored. Instead, we will discuss another type of reasoning, namely 'visuospatial reasoning', which plays an important role in science and science education (Ramadas, 2009).

5. *Visuospatial reasoning*: You might have noticed that the first three kinds of reasoning are used on the information which is presented either through

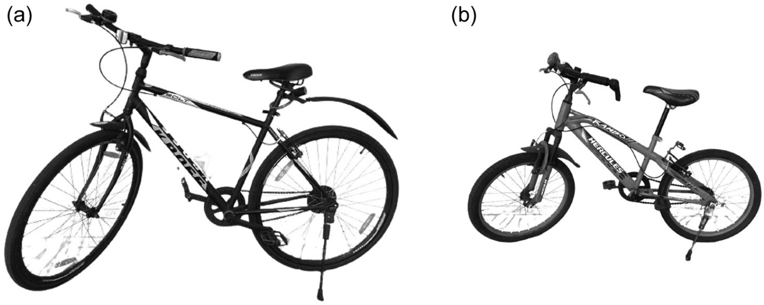

FIGURE 3.3 a/b An example of visuospatial reasoning: Which of the two bicycles will go farther with the same number of times of pedalling (provided the gear ratio of the two cycles is the same)? Source: Illustration by Ramesh Prakash Khade.

sentences or through equations. Both sentences and equations are kinds of propositions. Hence induction, deduction and abduction are kinds of propositional reasoning. However, not all information stored in our minds is propositional. We also store information in the form of mental images. Images mainly include visual information such as colour and brightness and spatial information such as shape, size, distances and motion.

For example, if I ask you to recall how your first bicycle looked, you will recall its colour, height and how it moved, even if it is not in front of you or you may not have even seen it in years. Now see the images of the two bicycles in Figure 3.3 and answer this question: Which of the two cycles will go farther with the same number of times of pedalling (provided the gear ratio of the two cycles is the same)? If you inferred that the cycle with the larger wheels will go farther away, you have used the spatial information in the two images to draw an inference. This kind of reasoning is called visuospatial reasoning. Visuospatial reasoning plays a crucial role in science, engineering, designing and mathematics. We will discuss this in detail in the innovative pedagogy presented in the next section.

Problem Solving

Problem solving is a complex cognitive task which requires both concepts and reasoning. Learning to solve problems is often considered one of the main aims of learning physics. Knowledge about concepts and the ability to reason together contribute to the ability to solve problems. If we consider a broader meaning of the term 'problem solving', there are several types of problems and whether 'problem solving' is a generic skill is a question (Maloney, 2011). Nonetheless, as a part of learning physics, students are required to learn to solve certain types of well-defined problems from high school onwards and it has been documented to be one of the difficult skills to teach. Current studies focusing on problem solving tend to be at the college level rather than the school level. However, there are some important results from the problem-solving literature of interest to school teachers (Ince, 2018):

1. Problem solving improves conceptual understanding.
2. Physics achievement and problem-solving strategies do not depend on gender.
3. Preservice teachers fail to use strategic solution approaches to solve problems.
4. Contextually rich problems motivate students to solve them.
5. Motivation influences metacognitive planning and problem categorisation, which in turn, increase the ability of problem solving.
6. Students believe that problem solving is a linear process but problem solving requires self-monitoring and evaluation throughout the process. Metacognition plays an important role in problem solving.
7. Practice in problem solving (the number of physics problems solved) had no impact on students' performance on problem solving, academic achievement, self-confidence and understanding of concepts.
8. Teaching problem-solving strategies have positive effects on performance and attitude towards physics as well as physics self-efficiency.
9. Explanations about the correctness of the solutions are helpful.
10. Solving problems in collaboration (in groups/with peers) improves problem-solving skills, attitude towards problem solving and overall achievement. Peer tutoring has also been found to have a positive impact on students' problem-solving strategies, performance in problem-solving homework performance and physics scores.
11. Poor mathematical skills are the major obstacles in the domain of problem-solving skills in physics.
12. Verbalising problem-solving strategies and having a language for problem solving is helpful.
13. Pictorial expressions and graphics help students to better understand the concepts on which the problem was based, set up equations more accurately and evaluate the solution of the problem. Yet, students do not prefer to draw diagrams while solving problems.
14. Novice problem solvers focus primarily on solving the problem while expert problem solvers spend time on visualising the problem and use problem-solving strategies. 'Visualisation', one of the steps of problem-solving strategy, was the distinguishing feature of expert and novice problem solvers in this study.

Most of the studies on problem solving focus on problems which require deductive reasoning (with limited scope for drawing a diagram or visualisation in the beginning). However, some research on problem solving is done with non-conventional ways of reasoning such as reasoning through analogy or using diagrams like free body diagrams, PV diagrams, ray diagrams (Ince, 2018; Stieff & Raje, 2010; Padalkar & Hegarty, 2013) or using visuospatial thinking (Kozhevnikov et al., 2007; Padalkar, 2010).

ACTIVITY 3.5 ANALYSING PROBLEMS IN SCHOOL PHYSICS

Count the number of problems in the physics books (or chapters) from grades 8 to 10. Analyse them based on the following criteria:

1. How many problems were set in a context? Was the context familiar or of interest to students?
2. How many problems were accompanied by diagrams or encouraged students to draw diagrams?
3. How many problems were broad or open-ended (e.g., how can we find out the radius of a mustard seed or that of the earth) as opposed to problems which can be solved mechanically (e.g., mass and force is given and students are asked to calculate acceleration).

Spatial Cognition and Visual Representations

The models in science include information such as shapes, sizes, distances and trajectories. This kind of information is known as 'spatial' information which means 'relating to space'. Thus the ability to understand space, broadly known as 'spatial ability', plays an important role in constructing mental models and in visuospatial thinking. In fact, in a large scale longitudinal study, Wai et al. (2009) found that spatial ability is the strongest predictor of achievement and choice of occupation in science and technology-related fields. Therefore, the education system should make active efforts to nurture spatial ability among students along with linguistic and mathematical ability. Doing it through the experiences situated in science education and design and technology education seems most natural. Four such studies in Indian context are documented in Kunyakari et al. (in press).

To understand how representations help us in thinking, we will take help from one of the contemporary theories of cognition, namely 'information processing theory'. According to this theory, information is stored in long-term memory (equivalent to ROM in a computer) which has infinite capacity. To draw an inference we choose only relevant information and process it. This processing is done by working memory.[10] A kind of working memory which is responsible for processing spatial information is known as the visuospatial sketchpad. It plays an important role in processing spatial information or running a mental simulation to draw inferences. However, due to the limitation of spatial working memory, people often fail to process the spatial information or end up drawing an incorrect inference (just as we fail to mentally multiply two large numbers or come up with an incorrect answer due to the limitation of the phonological loop, i.e., the kind of working memory which processes propositions). Visual representations, such as diagrams, concrete models and animations can help in offloading working memory (this is again similar to writing down numbers and carrying out the multiplication instead of maintaining the numbers in memory and multiplying them at the same time). Therefore students need to be proficient in understanding and using multiple external representations (both spatial and propositional) and translating them into each other. For example, students should be able to draw a graph from an equation and vice versa in areas such as mechanics and thermodynamics. (For more discussion on representations and how they help in reasoning, see Padalkar, 2017). However, each of these external representations follows different conventions and there is ample evidence from the literature that they pose difficulty to learners. Students often need special instruction, enough time and practice to master each of the representations and relate it to other representations for the same system. The ability to use a variety of representations, singly and together, to think about and communicate scientific information is known as 'representational competence' (Kozma & Russell, 1997).

In the remaining part of this chapter, we will discuss the implications of research in some of the above focus areas in the context of an exemplar topic, namely astronomy. We will also see an example of innovative pedagogy based on an interface of mental models, model-based reasoning, visuospatial thinking and use of ICT.

Further Readings

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Ramadas, J., Chunawala, S., Natarajan, C. and Apte, S. (1996b). *Vidyarthyanchya Vidnyanavishayi Utsfoorta Kalpana: Ek Samshodhan Ahwal* (In Marathi) *(Students' Spontaneous Conceptions in Science: A Research Report)*, Mumbai: Homi Bhabha Centre For Science Education.

Exemplar Topic: Astronomy

Our quest about the origin of the universe and the laws that govern it has been a topic of contemplation since ancient times. Not surprisingly, as mentioned in the introduction, this gave rise to arguably the oldest branch of science: Astronomy.

Although it is limited to one or two chapters in the school science curricula, it has played a central role in the advancement of science, technology, our collective understanding of ourselves and nature and hence has a great impact on our society. A great amount of physics and mathematics has been developed to explain astronomical phenomena. For example, Galileo developed his framework of motion (Galilean relativity, acceleration due to gravity) to support the heliocentric model of the solar system.

Astronomy has the potential to teach students about nature of science, for students can make observations of commonplace astronomical phenomena such as phases of the moon, keep notes, identify patterns (e.g., the 30-day cycle and the relation between phase and the rising time of the moon), try to explain them based on the model they know (model-based reasoning), predict further observations and improve their models or explanations if necessary. Most of the explanations do not require advanced theoretical concepts (such as those from quantum mechanics) or mathematical formulation (such as calculus). It is true that it has limited scope for experimentation, and more emphasis on observation, but the entire universe is the lab of astronomy. Many of the substances (e.g., hydrogen) or phenomena (fusion) are first observed in astronomical context and then created in the laboratories. Some of them have not been recreated yet. The history of astronomy is full of dramatic episodes and also features a relatively higher number of women than other fields of physics and hence, has a great potential to be incorporated in the textbooks to shed light on the nature of science.

Moreover, astronomy warrants more careful consideration in the curriculum because of the close connection between astronomy and astrology. Students need to learn to distinguish between these two and embrace a healthy, rational worldview rather than living in the shadow of fear of the supernatural and adopting a fatalistic worldview. Students' inherent interest in the celestial bodies is an additional bonus to use as a starting point of formal science.

One of the most common approaches to learning astronomy is through observations. *Physics by Inquiry (Volumes I and II)* by Lillian McDermott (1996) and *Astronomy for the Enquiring Mind* by Eric Rogers (1982) are two excellent examples of observation-based curricula at the high school level. However, many of the justifications of models in astronomy or just to recognise the pattern in phenomena need observations at different locations taken at the same time or observations from the same location for an extended time period, or both. For example, one of the main pieces of evidence of the spherical shape of the earth comes from the observation that positions of stars are different from different locations on the globe at the same time. Or, to recognise the periodic pattern in the change of the path of the sun, one needs observations at least over a year. Such observations are, although desired, difficult to rely on in order to learn astronomy. More pragmatic pedagogic arguments are necessary to help students to construct mental models and explain phenomena based on them. In the section 'Example of Innovative Pedagogy', we will see another approach to teaching astronomy which relies on cognitive psychology. But before that let us see some research in astronomy education.

Alternative Conceptions in Astronomy

Astronomy is known to be prone to alternative conceptions. In this section, we will list some of the most prominent alternative conceptions documented in earlier literature. We will also include alternative mental models in the same list (summarised from Padalkar, 2010).

1. Alternative conceptions in observational astronomy:
   a. At any location at noon (12:00 pm) noon, the sun is directly overhead.
   b. We can often see planets at night but only with a telescope or a pair of binoculars.
   c. The pole star is the brightest star in the night sky.
2. Alternative models of the earth: The following four prominent models are documented.
   a. Flat earth.
   b. Hollow earth: We live inside.
   c. Earth is flattened at the top (people live only on the upper part).
   d. Dual earth: Spherical earth is some other planet in the sky (not the same as the one on which we live).

   Another related difficulty is that students do not have a formal notion of gravity or it is not combined with the spherical shape. This results in a notion such as that there are absolute vertical up–down directions. Many students also think that the direction north is 'straight up' (because of its vertical position on maps).
3. Alternative models of the sun–earth–moon system:
   a. A spinning earth model with the sun and moon at fixed positions on opposite sides.
   b. The sun and the moon move close to the earth and far away which results in a change in intensity of the light and in day and night.
   c. An orbiting sun and/or moon model, in which the earth is fixed.
   d. Both earth and moon orbit around the sun.
4. Alternative explanations of the day–night cycle: Some of the above models of the sun-earth-moon system already involve explanations of the day–night cycle. Apart from these, the following two explanations are also popular:
   a. The earth and the moon revolve around the sun every 24 hours.
   b. The sun and the moon revolve around the earth once every day.
5. Alternative explanations for seasons: Earth is closer to the sun in summer and farther away in the winter (due to its elliptical orbit).
6. Alternative explanations for the phases of the moon:
   a. The shadow of some object (a planet, or the sun or the earth respectively) cast on the moon causes the phases. The shadow of the earth falling on the moon is the most popular explanation of the moon phases at all levels including adults.
   b. Varying distance between the sun and the moon (moon near sun = full moon), varying distance between the earth and the moon (closer moon = full moon).

7. Other alternative conceptions about the moon:
   a. The moon shines because it makes light/it is like a star, just bigger.
   b. The surface of the moon is white (or brighter than the earth).
   c. People at different locations on the earth see a different phase of the moon during the same night.
   d. People often draw incorrect shapes of phases, particularly gibbous (Figure 3.4).
   e. It takes one day for the moon to go around the earth.
   f. The moon rises and sets every day at the same time.
   g. The moon does not rotate.
   h. We do not always see the same face of the moon.
   i. The shape of the moon's orbit is circular.
   j. Tides are caused due to only the moon's gravitational force.
8. The sun is at the centre of the universe.
9. A light year is a unit for measuring time. (Similarly, arcminutes, arcseconds, often referred to as minutes and seconds in astronomy, may also appear to be the unit to measure time, but it is a unit to measure angles.)

The other difficulty documented in the literature is that students do not have proper estimates of the distances, sizes and their proportions involved in astronomy. Astronomical distances are beyond perception and the sizes of astronomical objects such as the earth and the other planets are also very large (Feigenberg et al., 2002). As a consequence students fail to take account of consequences such as parallel rays coming from the sun or a distant star being parallel or the shape of a spherical object appearing flat.

Most of the alternative conceptions and difficulties mentioned here are found to be present among students from different cultural and geographical backgrounds. A developmental trend (percentage of students holding correct conception increases with age) has also been documented in many of these studies. Of course, this should be attributed to the number of years of schooling rather than to age since these studies are conducted on students (as opposed to out-of-school children).

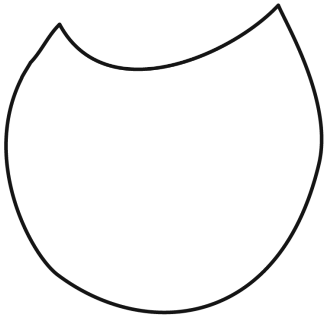

FIGURE 3.4 Incorrect shape of gibbous moon drawn by a student (recreated for printing purposes). Source: Illustration by Ramesh Prakash Khade.

Model-Based Visuospatial Reasoning in Astronomy

You might have noticed that in the list of alternative conceptions, there are several alternative models and incorrect explanations. As mentioned earlier the models include information about spatial properties (size, position, etc.) and other physical properties (temperature, electromagnetic field, etc.). The list of alternative conceptions shows that students may find it difficult to construct a mental model based on the information provided through text or diagrams. Thus visuospatial thinking needs to be strengthened in order to help students to construct mental models.

Explanations of astronomical phenomena are based on models (e.g., model of the sun-earth-moon system or model of the solar system), thus involving 'model-based reasoning'. Moreover, these explanations also involve visualisation and spatial thinking, together known as visuospatial reasoning. How can we foster this kind of reasoning among students? Let us see an example of an innovative pedagogy to strengthen visuospatial thinking to learn astronomy.

Example of Innovative Pedagogy

In this section, we will describe a blended module to teach astronomy and the rationale behind the design. We will also give a brief account of an experiment conducted to test the effectiveness of the module. The module 'Basic Astronomy' was prepared as a part of material development for the Connected Learning Initiative (CLIx). This is a blended module, which means part of it is to be taught in the classroom and part of it is for students to learn using computers. It is targeted at grade 8 or 9, since astronomy is taught in those grades in various state curricula as well as in the NCERT curriculum. It encourages teachers to adopt activity-based, interactive pedagogy and help students to engage in constructing mental models and visuospatial thinking through digital activities.

This module is based on the pedagogy proposed by Padalkar and Ramadas (2008, 2010). This pedagogy exploited the potential of three kinds of representations: concrete models, gestures and actions (can be also called role-plays) and diagrams. Concrete models and diagrams are well-known pedagogic tools in teaching science. On one hand, concrete models are three dimensional and can be made realistic and movable; they cannot be easily generated by the learner and are not suitable for reasoning or problem solving. On the other hand, diagrams can be easily generated by learners and are suitable for accurate inferences through geometric constructions but they are two dimensional, static and abstract and hence pose a problem to students (Padalkar, 2010).

Let us take an example. Suppose we want to teach how phases of the moon happen. We will see how it is dealt with in the corresponding lesson in the module (unit 2, lesson 2). Before we begin with the phases of the moon, students must know:

- motions of the moon (in particular revolution around the earth).
- sun rays falling on objects far away from the sun such as the earth and the moon can be considered parallel.
- basic concepts in geometry (sphere, tangent, circle, ellipse).

These are dealt with in the earlier lessons of the module.

The lesson on the phases of the moon starts with evoking students' observation of the change in the shape of the moon and introducing the term 'phases of the moon'. Then it is pointed out that even if the shape of the moon appears to change, the moon is spherical in shape. Half of it is always lit due to sun rays and half of it is always dark, just like the earth and any other spherical object.

Concrete model: We start with an activity which involves a concrete model which can be easily prepared. Students are asked to rotate a ball attached to a stick around them and observe it in a semi-dark room against bright light from one side. A bright torch light or a projector light works very well, but even light coming from a single window works fine. Here the ball acts as the moon, the student who is observing the ball is an observer on the earth and the torch light stands for the sun. A similar activity can be performed as a role-play instead of a model by replacing a ball with another student who rotates as the moon. This enables students to observe all phases of the moon except the full moon. Students are encouraged to represent this through a diagram at this point.

At the full moon position, students notice that their head (which is replacing the earth) blocks the light. If they have to move the moon slightly above the level of their head, they can see the full moon. It is explained that the moon's orbit is slightly tilted using an activity and a diagram. Because of the earth's rotation, the orientation of the inclination of the orbit changes with respect to the direction of sun rays. If the orbit is such that the moon is above or below the earth level we see the full moon, but if the moon goes through the earth's shadow we witness a lunar eclipse. A similar explanation is provided for the solar eclipse. At this point, students are encouraged to draw diagrams which explain the occurrence of eclipses. This clearly distinguishes the eclipses from the phases of the moon and addresses one of the main alternative conceptions that phases of the moon occur due to the shadow of the earth falling on the moon.

At the end, students are asked some intriguing questions such as: Can all people on earth see the same phase of the moon on any given day? Do the people in the southern hemisphere see the same phase of the moon as those in the northern hemisphere? Imagine that you are on the moon. How would the earth appear from the moon? Would you be able to see the phases of the earth?

This lesson is followed by a digital lesson. The digital lesson starts with animations of the revolution of the moon around the earth, the revolution of the earth around the sun and the revolution of the earth and the moon together. The second part of the digital lesson includes a digital game. This module includes a digital game called 'AstRoamer' and the second part of the game called 'AstRoamer: Moon Track' is based on the phases of the moon. Students are given clues about the phase of the moon on particular Indian festivals (which falls on that phase such as Budhha Purnima on the full moon, Diwali on the new moon and Eid on the first day of the waxing crescent) and students have to identify the position of the moon in its orbit. If students do not give the correct answer in the first attempt, detailed feedback and another attempt are provided. This game helps students to apply what they learnt in the earlier lesson in the familiar cultural context.

We hope this glimpse of the module will motivate you to go through the module and accommodate it in your teaching.

A Research Study to Test Effectiveness of the Module

Such pedagogies and modules must be tested for their potential before they are adopted into curricula. Padalkar and Ramadas (2010) had already tested their pedagogy in three schools serving underprivileged sections of society and found that it caused statistically significant improvement in students' understanding of astronomy (as compared to students who were taught using traditional pedagogy). However, the purpose of the module was to make this pedagogy widely available so that teachers can adopt it for their respective schools. Hence a study was conducted to evaluate the effectiveness of the module and to observe its implementation in the field closely. The study was conducted in seven government schools in the Jaipur district in Rajasthan. These schools were located in villages near Jaipur and served students from low educational and economical backgrounds. The teachers attended a one-day workshop twice during the course of implementation of the module (once in the beginning and once in the middle). The researchers visited the schools to observe the unfolding of the module and students' reception. They also provided on-site support to teachers whenever necessary (in addressing their doubts regarding content as well as pedagogy, conducting classroom activities and managing computer labs).

Students were tested before the intervention started (pre-test) and after the intervention (post-test). The seven schools where the module was implemented are called 'intervention schools'. Similar seven schools were selected where the same chapter was taught by the respective teachers using their traditional method. These are called 'non-intervention schools'. Pre-test and post-tests were administered on students in non-intervention schools as well and the classrooms were observed to note the qualitative differences in teaching and students' reception.

The teachers in the non-intervention group typically read the chapter from the textbook, explained some of the difficult terms and completed the chapter in two to three classroom periods. On the other hand, teachers from the intervention group incorporated several role-plays from the module and almost all digital activities. They completed the module in six to seven classroom periods.

The results show that there was no significant difference between the intervention and non-intervention groups to begin with (both scored about 32% in the pre-test). However, the intervention group significantly improved after

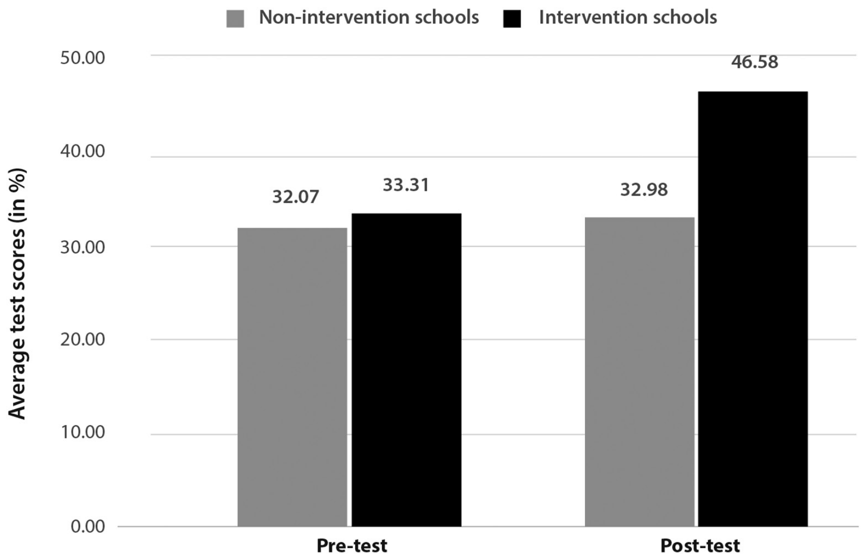

FIGURE 3.5 Scores in pre- and post-tests for the intervention group (who were taught using the Basic Astronomy module) and non-intervention group (who were taught in the traditional way). Source: Illustration by Ramesh Prakash Khade.

the intervention whereas the improvement in the non-intervention group was not statistically significant (Figure 3.5). The difference in the post-test scores between the intervention group and the non-intervention group turned out to be significant. Thus the module is seen to be significantly better than the traditional methodology. Detailed findings of this study are available in Shaikh et al. (2020) and CLIx (2019).

It is important to note that the module does not require any extra equipment and can be easily carried out in regular settings.[11] The time requirement was also kept equivalent to the number of lessons typically allocated to the respective chapter in the textbook. Moreover, teachers can pick and choose the activities which are more aligned with their curriculum. The only things teachers need to adopt such pedagogy is a firm grip on the content and an imagination to visualise alternative classrooms where students are conducting structured activities, discussing and freely expressing their thought through speech, gestures, drawings and any other possible ways, instead of sitting on the bench, listening to what teacher says and giving only correct answers.

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SUMMARY

In this chapter, we learnt:

- The scope of physics is vast, from subatomic particles to galaxies and the universe.
- Empirical research (experiments and observations) and theoretical research are the two pillars of scientific knowledge.
- Research in physics education aims to identify students' understanding prior to any instruction, proposes different innovative methods of instruction and assesses their effectiveness and tries to understand how we learn about the physical world and why certain instructional methods are effective.
- Children often form intuitive notions about the physical world from their experiences. They need to be taken into account while teaching.
- Alternative conceptions are robust and often do not eliminate after instruction. However, conceptual change is possible when students are dissatisfied with their prior conceptions and an available replacement conception was intelligible, plausible and/or fruitful.
- Mental models are another important mental representation in science. Students may also have alternative models and change in alternative models needs holistic comparison of alternative and scientifically accepted models.
- Different kinds of reasoning play an important role in drawing inference. Induction, deduction, abduction and analogical reasoning play an important role in explanations and predictions. Visuospatial reasoning is newly identified as an important form of reasoning. In visuospatial reasoning, visual and spatial information is transformed mentally or using external representations such as diagrams or simulations to draw inferences.
- Problem solving and conceptual understanding are interdependent. Some of the factors which improve problem solving are: Setting the problems in context, providing (or encouraging students to draw) pictorial representations, teaching problem-solving strategies, providing explanations for correct solutions and letting students solve problems in collaboration. Problem-solving ability does not depend on gender and practice. Poor mathematical skill is an obstacle in problem solving.
- Astronomy, despite being seemingly easy and interesting, is prone to generate alternative conceptions. Students also have alternative models

about the earth and the solar system. A sequence of spatial representations (concrete models, gestures and role-plays, digital animation and diagrams) can be fruitfully used to help students to construct scientifically accepted mental models and provide explanations of commonplace astronomical phenomena based on them.

Exercises and Practice Questions

1. Take any four topics in school physics and identify five prominent alternative conceptions from them. Refer to the relevant literature from the further readings provided at the end of this chapter. Interact with a few children to compare with the five prominent alternative conceptions you identified in the literature.
2. Give two examples of each from school physics: Induction, deduction, abduction, analogy and visuospatial thinking.
3. Create an innovative pedagogy for your favourite topic:
   a. In this chapter, we discussed an innovative pedagogy to teach astronomy. Since students face problems in visuospatial thinking this pedagogy emphasised the use of visuospatial representations.
   b. Choose your favourite topic in physics. Prepare a diagnostic test to pin down the alternative conceptions and other difficulties in that topic.
   c. Identify possible difficulties in learning this topic. Design a pedagogy to address these difficulties and the alternative conceptions which you may encounter.
   d. Devise ways to test the effectiveness of your pedagogy. Which tools will you use to assess students' knowledge after the instruction (e.g., preparing concept maps, conducting an experiment, problem solving, building a three-dimensional model, preparing a circuit, etc.). What questions will you ask while you are teaching? What will you observe and note down (students' questions, notes, drawings, discussions)?

Notes

1 Empirical: Based on or verifiable by observation or experience rather than theory or pure logic.
2 Karl Popper (1902–1994), a philosopher of science, identified 'falsifiability' as a criterion to determine whether a theory is scientific or not. He claimed that fields such as astrology and psychoanalysis are not sciences because their theories cannot be falsified. He called them 'pseudosciences'. This is discussed in Chapter 2.
3 Scientific modelling is a scientific activity, the aim of which is to make a particular part or feature of the world easier to understand, define, quantify, visualise or simulate by referencing it to existing and usually commonly accepted knowledge.
4 It must also be noted that the processes involved in physics (or science) and technology are different, with more analytical thinking involved in the first and more designing involved in the later.

5 'Gender and science' studies identify the difficulties and barriers faced by girls in studying science and find ways to make girls more comfortable in learning science.
6 There are a few studies which show how culture influences alternative conceptions but they are mainly in the area of astronomy where cultural beliefs are in contrast with scientific knowledge. See Samarpungavan et al. (1996), for example.
7 An example of tree structure of concept: Entities can be divided into living and non-living. Living beings can again be divided in domains: Archaea, Bacteria and Eukarya. Eukarya can be further divided into five kingdoms: Plantae, Protista, Animalia, Chromista and Fungi. Each of the kingdoms can be further divided into multiple phyla and so on.
8 Abductive reasoning was formally advanced by an American philosopher Charles Peirce (1839–19 April 1914).
9 For more information, visit https://plato.stanford.edu/entries/scientific-method/
10 Working memory or short-term memory is equivalent to RAM in a computer. It is responsible for processing the information (e.g., adding two numbers or comparing which of the two pencils are longer). It has a limited capacity and can hold information temporarily.
11 Computers are now available in school computer labs; however, maintaining the lab and enabling students to use it is still not part of culture in many schools.

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4

AN INQUIRY-BASED APPROACH TO LEARNING CHEMISTRY

> I lamented that the spirit of inquiry had died out amongst a nation naturally prone to speculation and metaphysical subtleties. Little did I dream that in the course of a decade or so I should have to revise the estimate I then formed of my own countrymen and chronicle that a bright chapter is about to dawn in our life history.
>
> P.C. Ray (1918: 45)

OBJECTIVES

The objectives of this chapter are to help you:

- develop an understanding and appreciation for the discipline of chemistry.
- become familiar with the historical and philosophical developments leading up to the modern scientific discipline of chemistry.
- give an overview of chemistry concepts in the Indian school curriculum.
- introduce pedagogical content knowledge in chemistry and build a justification for why teachers require the same.
- introduce inquiry-based teaching.
- provide detailed examples for the teaching of chemical reactions using the inquiry-based approach.

DOI: 10.4324/9781003047506-5

The chapter is organised as follows:

- What is Chemistry?
- Some Key Concepts in Chemistry
- Development of Chemistry
- Chemistry as a School Subject
- Inquiry-Based Teaching
- Pedagogical Content Knowledge
- Teaching Chemical Reactions: An Inquiry Approach
- Summary (Figure 4.1)

What Is Chemistry?

In the 21st century, chemistry has become the largest scientific discipline, producing over half a million publications a year ranging from direct empirical investigations to substantial theoretical work (Weisberg et al., 2019). Let us take a brief look at what the discipline of chemistry is about. Chemistry can be considered to be the science of the transformation of substances. It deals with the composition and constitution of substances and the changes they undergo. While studying the properties and transformations of substances, chemists may discuss phenomena that occur at the micro level and involve concepts like atoms, electrons, molecules, etc. They may also study substances at the macro level using concepts such as energy, entropy and enthalpy from thermodynamics (Van Brakel, 1997).

'Chemistry can be defined as the science of the characteristics of (macroscopic) materials or phases (including phase transitions) and their containing (molecular-scale) species, as well as the (planned) interaction of these materials with other materials (synthesis, chemical transformations, separation methods)' (Van Brakel, 2014). Chemistry is thus a unique discipline that is concerned with characterising material or stuff, understanding the phases in which material can exist in or

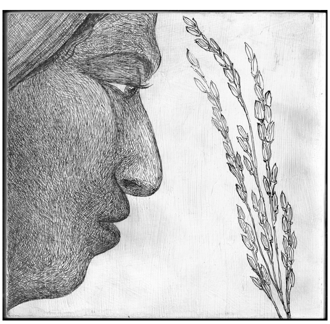

FIGURE 4.1 Inquiry begins with systematic observation. Source: Illustration by Karen Haydock.

be transformed into and synthesising new material. The modern Chinese word for chemistry means 'science of material change'. This captures the importance of synthesis in chemistry. Synthesis is central to organic, polymer, inorganic, organometallic and solid-state chemistry. 'Unlike other branches of science, the scientific products of synthetic chemistry are not merely ideas, but substances that change the material world, for the benefit or harm of living beings' (Van Brakel, 2014). Let us pause and think whether this is a far-fetched claim. What is being said, is that a large part of work in chemistry involves synthesising new material. Through the work of chemical synthesis, material that did not exist previously in the world is produced – for example, detergents, plastics, ceramics, drugs, etc. The list gets longer and more complex every day. Thus chemists are constantly creating new substances whose properties have to be studied and understood in terms of the various positive and negative impacts that these can have.

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Some Key Concepts in Chemistry

Since we can think of chemistry primarily as the science of substances and their transformations, it will be useful to discuss the idea of a 'substance'. The idea of a substance overlaps with other ideas such as 'stuff' and 'material'. When Archimedes was trying to come up with a method to decide whether the king's crown was made of pure gold or alloyed with another metal, he was using the notion of a pure substance. We think of pure substances as having invariant characteristics that distinguish them from other substances. A lot of early work in chemistry and its precursor, alchemy, was concerned with purifying substances. Even to this day, school chemistry textbooks begin by giving students a quick overview of various purification techniques. Materials are identified by using their properties such as taste, density, composition, melting point, reactivity, etc. Such properties are independent of the shape, size and mass (within certain ranges) and may be identified by using some kind of observation or measurement. Materials which have the same properties but differ in size and shape are considered to consist of the same substance. Further, if two randomly chosen parts of some material display the same characteristics with respect to a chosen set of properties then the material is said to be homogenous. Homogeneity is relative to the accuracy and scale of observation. In the case of glass, transparency and uniform colour suggest homogeneity. However many glasses are inhomogeneous at levels from a few nanometres up to a few micrometres (μm).

Another important idea about substances dating back at least from the time of Aristotle is that a single substance – for example, water or gold – can exist in different phases or states. Water as we know can exist as ice, or water or steam.

Thus the notion of substance suggests something that is invariant across physicochemical phase changes. These phase changes can be reversed by heating or cooling and can be distinguished from chemical transformations which result in the formation of a new substance/substances (Van Brakel, 2012).

Associated with the idea of substances are the notions of pure and mixed substances. A pure substance is actually a theoretical abstraction derived from empirical processes used to obtain a substance that is homogenous and cannot be further separated into other substances using purification techniques. In actual terms, it is almost impossible to get an absolutely pure substance. Further, at the microscopic level, this substance may not be homogenous. Nevertheless, the idea of a pure substance is a useful concept and gives us a way of characterising the substance while distinguishing it from other substances. Somewhat connected to the idea of a pure substance is the idea of an element. Everyday materials are often complex mixtures of many substances.

Substances themselves are thought to be made up of elements. Elements from ancient times have been thought to be the basic components of all substances. The Vedic, Buddhist and Jaina philosophies theorised that all substances could be considered to be made of a few basic elements. In the Vedic literature, we find reference to five elements – or *pancha bhutas* – and they are *prithvi*, *ap*, *tejas*, *vayu* and *akasa*. These may be designated respectively as earth, water, fire, air and a non-material ubiquitous substance. The Greek philosopher, Aristotle, held that the elements fire, water, air and earth were the building blocks of all substances. In Wuxing, the Chinese philosophy used to describe interactions and relationships between things, the five elements – wood, fire, earth, metal and water – are believed to be the fundamental elements of everything in the universe between which interactions occur. Modern chemistry has identified over 100 elements which are organised in the periodic table.

How to relate the categories of pure substances to the conceptual notion of elements? The latter finds its empirical base in the existence of simple substances that cannot be separated into other substances, under normal experimental conditions. A pure substance may or may not be decomposable into two or more simple substances. If it is not decomposable, it can be said to be an element. If a pure substance can be decomposed into simpler substances (or elements) then we term it to be a compound. We may be used to thinking of compounds as substances that are composed of two or more elements that are combined together in a fixed proportion – in other words, stoichiometric compounds. In reality, there are many kinds of substances apart from elements and stoichiometric compounds such as allotropes, non-stoichiometric compounds, isotopes, inclusion compounds, addition compounds, polymers, enantiomers, racemates and tautomers.[1] The endnote provides definitions of some of the substances in this list. Douglas, McDaniel and Alexander (1994) is a good reference in chemistry to find out about the others.

If elements have been thought of as basic components of various substances, there has been another long tradition in philosophy of science – that of atomism.

Atomism, or the concept that matter is ultimately made of indivisible building blocks, appeared in India a few centuries BCE as part of philosophical speculations, in particular in the Vaiśeṣika, one of the six philosophical systems of ancient India. In this system, all substance was seen as an aggregated form of smaller units called atoms (*aṇu* or *paramāṇu*), which were eternal, indestructible, spherical, supra-sensible and in motion at the primordial state; they could form pairs or triplets, among other combinations, and unseen forces caused interactions between them. The idea of chemical atomism is associated with the 19th-century work of John Dalton (1766–1844). Of course, Dalton's original postulates regarding atoms as the smallest, indivisible particle of an element has undergone many changes. By the beginning of the 20th century, scientists had discovered that atoms were made of smaller particles like electrons, protons and neutrons. Modern chemistry and physics have given us an idea of atomic structure and many phenomena in chemistry use ideas about atomic structure to explain properties of substances as well as chemical reactions.

Development of Chemistry

Modern chemistry took shape in 18th-century Europe, after a few centuries of alchemical traditions which were introduced in Europe by the Arabs. Some recent studies by historians of science have shown the importance of alchemical practices in creating the foundations of modern chemistry. The presence of the Arabic definite article *al* in *alchemy* is a clear indication of the Arabic roots of the word. As the Arabs started expanding territorially in the 7th century they were open to learning from already extant civilisations. Many classic texts dealing with metallurgy and medicine preparations from Egyptian and Greek sources were translated into Arabic. The Arabs later spread this knowledge to Europe. In medieval times, alchemy was a secretive practice whose ultimate goal was to turn base metals into gold and discover an 'elixir of life' that would grant immortality.

The ancient Chinese and Indian cultures had alchemical traditions of their own, which included much knowledge of chemical processes and techniques. In India, we can trace such techniques all the way to the Indus civilisation (3rd millennium BCE) and its antecedents. In medieval India, chemical knowledge was codified as *Rasayan Shastra*, *Rastantra*, *Ras Kriya* or *Rasvidya*. It included metallurgy, medicine, manufacture of cosmetics, glass, dyes, etc. Some of these texts are still available to us and a few of them have been translated into Arabic at the behest of the Caliphs (Ray, 1902).

An early conceptual analysis concerning matter and its transformations comes to us from Aristotle and his followers. Aristotle gave us one of the early philosophical bases to develop further understanding about elements, pure substances and chemical combinations. He wrote some of the earliest systematic treatises related to chemical theory.

It is thought that Khalid ibn Yazind, who died around the beginning of the 8th century CE, commissioned the first translations of alchemical treatises from Greek and Coptic sources into Arabic. Towards the latter part of the century, the Arab, Jabir ibn Hayyan, had produced the *Corpus Jabirianum* – an impressive alchemical treatise. We have the Arabic alchemical tradition to thank for transmitting the legacy of the ancient worlds to medieval Europe (Ferrario, 2007).

Chemistry developed mainly in the form of alchemy and iatrochemistry[2] during 1300–1600 CE. Alchemists were mainly concerned with finding ways to produce gold from other materials on the one hand and to find ways to prolong healthy life on the other. The second aspect involved the application of chemical/alchemical understanding to medicine and is referred to as iatrochemistry. Modern chemistry took shape in 18th-century Europe, after a few centuries of alchemical traditions which were introduced in Europe by the Arabs.

The Frenchman, Antoine Lavoisier (1743–1794), may well be considered one of the key founders of modern chemistry. In 1789 he had made a list of the elements that a modern chemist would recognise. On the basis of his experiments, he postulated that mass is conserved in a chemical reaction. In England, John Dalton (1766–1844) postulated that each element was made up of atoms and that atoms of an element were all alike.

Further experiments by different scientists led to the discovery of many new elements in the 19th century. For example, Humphrey Davy (1778–1829) isolated sodium and potassium by electrolysis. The list of elements kept changing and growing. Chemists soon felt the need to come up with a way to systematically order the various elements and were in search of a suitably typology of elements. Many attempts were made in this direction – notable among them were Dobereiner's grouping of elements with similar properties in groups of three called triads based on his observations of the alkaline earths; namely, that strontium had properties that were intermediate to those of calcium and barium. In 1865, English chemist Newlands noticed that if elements were arranged in order of their atomic weights, every eighth element showed similar chemical and physical properties – rather like *sa*, *re*, *ga*, *ma*, *pa*, *da*, *ni* and *sa* again. Building on the idea of octaves, Russian chemist Mendeleev published his periodic table in a form that was very close to the modern periodic table. This table was organised on the idea of periodically recurring general features as the elements are followed when sequentially ordered by relative atomic weight.

A major challenge to the periodic arrangement of elements came from the radiochemist Frederick Soddy (1877–1956) in 1913. Going strictly by the atomic weight criterion would mean that the same positions in the periodic table were occupied by several elements. Soddy called these elements 'isotopes', meaning 'same place'. Around that time, Bohr argued that the atom consists of a positively charged nucleus around which much lighter electrons moved in fixed orbits or shells. After some discussion about criteria (van der Vet, 1979), delegates to the 1923 IUPAC meeting saved the periodic table by decreeing that positions should be correlated with atomic number (number of protons in the nucleus) rather than atomic weight.

Modern chemists continue to delve into the way atoms interact with each other by forming chemical bonds of various kinds. Theory building around how the various subatomic entities come into play to give rise to different materials and substances by way of reactions and phase changes is an ongoing endeavour. At the same time, the traditional concern of chemistry with synthesising and characterising material has given rise to an ever-increasing space of study.

Further Readings

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ACTIVITY 4.1

Make a timeline of the evolution of early technologies in India from about 10,000 BCE to and including the Ganges civilisation.

Chemistry as a School Subject

According to the NCF (2005), chemistry as a separate discipline or subject for study is to be introduced only at the higher secondary level. Syllabi from other examination boards such as the AICSE introduce chemistry as a separate subject by grade 8. Regardless of when the subject is introduced formally as a separate area of study in schools, children are introduced to many concepts related to chemistry from grades 5 or 6. Even before that, children may have been taught about different substances when teachers ask them to identify objects made of wood, metal, cloth, paper, plastic and glass. Children in primary grades would also have learnt about water and how some substances dissolve in water and others do not. They would have learnt about phase changes while studying the water cycle. Thus by grade 6, children typically would have learnt many concepts and developed some schemas for thinking about substances. These schemas will need to be further developed and elaborated as children move through middle and high school.

Let us take a look at the chemistry-related chapters in the NCERT books from grades 6 to 10. In grade 6, Chapter 4: Sorting Materials into Groups draws attention to the materials that make up everyday objects and introduces children to properties of different materials. Chapter 5: Separation of Substances builds on the idea of different materials/substances discussed in Chapter 4 and further develops the notion of mixtures of substances that can then be separated into their components. This will lay the ground for further discussion about the different ways in which substances can mix, combine, change and transform. Chapter 6:

Changes around Us helps children explore the different ways in which materials can be transformed and brings in the notion of reversible and irreversible changes. These ideas as we saw in the first section are at the heart of chemical theories. Chapters 14 and 15 introduce children to water and air respectively. It is interesting to speculate why these units have been included. Perhaps the importance of air and water to our lives was what led the ancient Indians to consider them as elements and may be that is the reason for introducing these topics in the grade 6 science textbook. Of course, the ancient notion of air and water as constituent elements of different substances is very different from the actual air and water and the way we think about these in modern science.

In grade 7, Chapter 5: Acids, Bases and Salts takes children further into exploring properties of substances and without explicitly stating so, this chapter invites children into thinking about how substances react with each other and how chemical transformations occur. Chapter 6 deals with chemical and physical changes and extends the conceptual schema developed in Chapter 6 of the previous grade.

In grade 8, students are introduced to some of the material science aspects of chemistry through Chapter 3: Synthetic Fibres and Plastics. In the previous two grades, students had been introduced to fibres and their importance in our lives. In grade 8 students will be able to see how our understanding of chemical reactions has helped us develop synthetic substances. Chapter 4: Metals and Non-metals, while revisiting properties of substances, develops a more formal understanding of substances as elements and also introduces a typology of elements. Chapter 5: Coal and Petroleum is another exploration of materials that are important energy sources and thus introduces students to both the material aspects as well as the energetics involved in chemical transformations. This is further extended in Chapter 6: Combustion and Flame. Chapter 14: Chemical Effects of Electric Current delves into another aspect of chemical transformations and how they are related to electrical phenomena.

In grade 9, Chapter 1: Matter in Our Surroundings introduces the concepts related to the particulate nature of matter and the empirical basis for the same. It is interesting to note that in a departure from other textbook series, the latest NCERT textbook series introduces this only in grade 9. This may be pedagogically more justified. Teaching children about the particulate nature of matter too early seems to produce some degree of confusion and also results in alternative conceptions. Introducing the idea of atoms too early to children allows for a number of alternative conceptions to develop. Typically, many textbooks introduce the idea of atoms and subatomic particles by grade 7 or 8 and children are even made to draw orbital diagrams of electrons at this early stage. In doing so, children develop rather static ideas about atomic structure and tend to think of subatomic entities like electrons as more or less rigid and solid entities. They also learn to think of orbitals as fixed paths, rather like the paths traced by planets in the solar system. Although this is a useful model to explain the reactivities and valencies of elements, the idea itself is problematic and in higher classes, students will need to discard this notion altogether as they learn about quantum theory. This problem is not addressed in grade 9, Chapter 4: Structure of the Atom, although this chapter does give a brief history of how ideas about atomic structure were developed.

Chapter 2: Is Matter around Us Pure? elaborates and extends the concepts and schema developed in grade 6, Chapter 5 and establishes the formal definitions of elements and compounds. Thus the NCERT textbooks seem to be loosely following a spiral curriculum. Chapters 3 and 4 of grade 9 develop ideas about atoms and atomic structure and also show how these ideas have helped us to understand chemical phenomena. Chapter 3 introduces another important concept – that of molecules – in a simple way. The notion of a molecule is a complex one and there are several ambiguities associated with this notion. One may debate whether we should bring in these ambiguities at this stage of learning. However, as a teacher, you need to delve more deeply into the concepts related to the word 'molecule'.

The spiral curriculum approach is continued in the grade 10 textbook. Chapter 1: Chemical Reactions and Equations extends and elaborates concepts of chemical changes from grade 5 and grade 6 and also integrates it with concepts related to shorthand notations for elements learnt in grade 9. Chapter 2: Acids, Bases and Salts extends what was learnt in grade 7, and Chapter 3: Metals and Non-metals takes further what was introduced in grade 8. Chapter 4: Carbon and Its Compounds introduces students to organic chemistry. Chapter 5: Periodic Classification of Elements brings together many of the concepts learnt in grade 9 and presents one of the most important ideas in chemistry.

By now, it is evident that a fair amount of formal chemistry has been introduced to students by the time they finish grade 10. Even if the CBSE board does not have a separate examination for chemistry as a subject, the chapters in the textbook are so organised that ideas related to chemistry as a discipline are clearly discernible. In some cases, like the chapter on synthetic fibres in grade 8, the application of chemistry to other areas is highlighted. It is desirable for students to be able to make conceptual links between the various chapters in their science textbooks and perhaps even across other school subjects.

Further Reading

NCERT syllabus for Elementary Classes (2006), NCERT syllabus for Secondary and Higher Secondary Classes (2006).

ACTIVITIES

1. Read the science textbooks of grades 6 to 10 in your state. Which vision of science curriculum organisation do they adapt (refer to Chapter 1)?

2. On page 53 of the grade 9 NCERT science textbook we find this assertion: 'Chemical properties of all the isotopes of an element are the same'. Would you agree? Does this bring into question the definition of an element?
3. Is it possible to talk of a molecule of sodium chloride? If so, what exactly would a molecule of sodium chloride refer to?

Inquiry-Based Teaching

There are many approaches to teaching science, and among them, the inquiry-based approach has considerable support from science educators. 'A good pedagogy must essentially be a judicious mix of approaches, with the inquiry approach being one of them' (NCERT, 2014).

Let us briefly discuss what is meant by inquiry and how it can be used in teaching.

> Scientific inquiry refers to the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. Inquiry also refers to the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world.
>
> *(National Research Council, 2000)*

Scientific inquiry is an extension of human curiosity. Most of us would have observed young children being curious and trying to find out for themselves about various things in their environment. Some children may not express their curiosity verbally, but would be engaged in actively exploring some aspect of their environment – maybe ants, objects or tools. Many children also have a tendency to keep on asking questions about the world around them. More often than not, the adults around them do not encourage this and after some time children become silent and some even give up trying to learn more may end up becoming quite disinterested. Forcing them to learn a string of facts about various natural phenomena without sparking their natural curiosity is a very uninspiring and even counterproductive way of teaching. Facts learnt this way will soon be forgotten and will be rarely used to solve real-life problems. In many of our schools, it is still observed that 'there is too much emphasis on drill and rote learning and too little emphasis on observation, design, analysis, argumentation and process skills in general' (NCERT, 2014). The NCERT (2014) position paper on science argues that textbooks must themselves be written in such a way as to promote curiosity by raising open-ended questions and encouraging students to explore and find out for themselves. Following the NCF 2005 guideline, the NCERT textbooks to a large extent support inquiry-based learning and teaching.

Science education should provide students to develop the following kinds of scientific skills and understandings:

- learn about scientific concepts and principles.
- acquire the reasoning and procedural skills of scientists.
- appreciate the nature of science as a particular type of human effort.

In the inquiry-based approach, students learn to formulate ideas and explanations about specific phenomena and then carry out simple investigations to test out their ideas. In doing so they will be able to learn many scientific concepts and principles and also reasoning and procedural skills. Studies show that students are much more likely to retain concepts learnt in this manner. At the same time, they will develop first-hand experience of scientific methods and practice. This will also enable them to get a sense of the nature of science. Ideally, inquiry-based teaching will help students learn science, learn to do science and learn about science.

Research on learning indicates that students need to develop abilities to inquire. Basically, all students need to learn how to think scientifically. This means that they should be able to observe a phenomenon – for example, a candle burning – carefully and be able to articulate what they think may be going on – in other words, give an explanation or propose a hypothesis. Instead of observing a phenomenon, they may equally pose a problem. For example, they may be interested in why milk goes bad if left unrefrigerated. Here too the first step would be to observe carefully and describe what is happening. After developing a tentative explanatory hypothesis – often in the form of a causal mechanism, the next step would be to investigate whether their ideas are supported by further experimentation and investigation. While developing an investigation strategy students will need to think of what data would be relevant and admissible in the light of the phenomenon/problem being investigated, they would then need to carry out the investigation and analyse and interpret the data. This process can work well if students work in groups. Alternative hypotheses may be suggested by group members and the validity of the argument put forth by any one child could be questioned by others, thus strengthening the group's ability to reason out. Through scientific inquiry, students can gain new data to change their ideas or deepen their understanding of important scientific principles. They also develop important abilities such as reasoning, careful observation and logical analysis.

Students form ideas and conceptions about the various phenomena that they experience even without receiving explicit instruction in the classroom about these. Indeed, not only students, all of us have such conceptions and we would not be able to act upon the world without these conceptions forming part of elaborate and complex networks of mental schema. In the case of students, if these preconceptions are consistent with scientifically accepted ideas then they can serve as the basis for building deeper understanding in the course of formal education. However, more often than not, students' preconceptions are inconsistent with accepted scientific knowledge. These alternative conceptions do provide students with a more or less coherent operational understanding of phenomena, even if they are inconsistent with more scientific explanations of the phenomena. Student alternative conceptions can be quite persistent, especially when they are taught through conventional methods. Students may apply their conceptions to situations where they do not work (Anderson & Smith, 1987; Driver et al., 1985, 1994). For example, Schollum (1981), in a study, found that around 70% of 14-year-olds and over 50% of 16-year-olds thought diluting a strong fruit juice drink by adding water was a chemical change. Schollum also found that 48% of 14-year-olds and 55% of 16-year-olds thought sugar dissolving was a chemical change. It is also not uncommon for teachers to have their own alternative conceptions. There is a great deal of research on students' conceptions about science-related matters across many disciplines (Driver et al., 1985, 1994; Minstrell, 1989, 1992; Novak, 1987). Duschl and Gitomer (1991) suggest that the extent to which learners change their ideas depends on what they consider to be evidence for or against a competing idea.

> Inquiry focuses on a scientifically oriented question, problem or phenomenon, beginning with what the learner knows and actively engaging him or her in the search for answers and explanations. This search involves gathering and analyzing information; making inferences and predictions; and actively creating, modifying and discarding some explanations. As students work together to discuss the evidence, compare results, and, with teacher guidance, connect their results with scientific knowledge, their understanding broadens. As they develop their abilities to question, reason and think critically about scientific phenomena, they take increasing control of their own learning. They can use their broadened science knowledge and inquiry abilities to address other questions and problems and to develop or test explanations for other phenomena of interest. In this way, effective learning involves the reorganization of the deep structure of one's thought processes. The learner comes to own a new idea or new way of thinking. Without this, school learning becomes a transitory experience with little application to future thought and action.
>
> *(National Research Council, 2000: 120)*

However, as the NCERT position paper on science teaching (NCERT, 2014) points out, there can be problems associated with the inquiry-based approach to science teaching. In scientific inquiry, experiments are motivated by a theory or a hypothesis. Drawing inferences from observations is not a straightforward or obvious process. Interpretations of the observations are based on the underlying assumptions or theories. In the classroom situation, experiments are typically motivated by the teacher or the textbook. Students either watch demonstrations or are told what to do. They are also instructed about what observation to focus on and the inference is also pre-determined. This does not promote genuine inquiry on the students' side. For inquiry-based science teaching to be effective, there must be sufficient opportunities for the teachers and students to discuss ideas, plan experiments to test out ideas, record observations and come up with possible explanations based on evidence and reasoning.

An expert chemistry teacher needs to have conceptual clarity and awareness of students' alternative conceptions related to the concepts taught. Alongside this, the teacher also needs to develop the capacity to transform chemical concepts in such a way as to promote understanding of the same among students. In other words, the teacher needs to have pedagogical content knowledge (PCK).

Further Reading

National Research Council. (2000). *Inquiry and the national science education standards: A guide for teaching and learning*. The National Academies Press.

> **ACTIVITY 4.2**
>
> Describe and if possible carry out an inquiry-based lesson on any topic from chemistry and record the students' discussions and include your own responses as a teacher. Reflect on your experience and on the process of inquiry-based teaching.

How can inquiry-based teaching be made effective?

Pedagogical Content Knowledge of Chemistry

As teachers begin their careers and face the challenges of teaching topics in chemistry, they develop pedagogical content knowledge in chemistry that enables them to create the appropriate classroom/laboratory environment, encourage student thinking and come up with the tactics that increase student understanding of the chemistry topic being taught. An inquiry approach can serve as the hook by which teachers can capture student attention and promote conceptual change in chemistry. The specific ways in which a teacher sets up and coordinates inquiry-based lessons for a particular chemistry topic form part of her PCK.

> Ideally, Shulman (1986) says, the teacher will transform disciplinary knowledge to encourage understanding of meaning by his/her population of students. Transformation is an explanatory process that differs from giving an explicit restatement of the chemical view of a concept or theory and expecting students to remember it. Teachers must figure out what it

> means to transform chemical knowledge on specific topics that explains chemistry at the level of their students.
>
> *(Bond-Robinson, 2005)*

Let us discuss how children are taught to think about physical and chemical changes. One of the criteria that children are taught to associate with a physical change is that such a change is reversible. Examples of water evaporating and then condensing may be demonstrated to show the reversibility of the change in the state of water from liquid to vapour and back again. Several alternative conceptions persist in children's minds about physical and chemical changes. Many children associate change of phase, such as dissolving, or change of state, such as evaporating, with chemical change (Ahtee & Varjola, 1998). Conversely, some children think that the burning of a candle involves a physical change since the wax melts and again solidifies on the sides of the candle. How can teachers transform chemical knowledge in order to bring about greater conceptual clarity in students? One strategy requires teachers to avoid making students learn formal chemical terms and definitions at the beginning and instead to present chemical events in a way which promotes students to think of explanations for what they see (deVos & Verdonk, 1985).

ACTIVITY 4.3

Read the following excerpt from a classroom and respond to the questions below.

In inquiry-based teaching with grade 9 students at an alternative school in Bangalore, students were asked to light a candle and observe it burning for some time. At one point after everyone noted that the candles were shorter after burning for some time, the question was posed about what happened to the wax. One of the students, Vinod, said that the wax had evaporated. Then the question of whether it was possible to collect the evaporated wax by holding a cold plate over the candle was posed, giving the analogy of water evaporating and again condensing on a plate held over the vapours. Vinod replied that in the case of the burning candle the wax changed and became something else and was not wax anymore – 'it becomes something else and we can't get it back'. This indicated that even though he had used the word 'evaporated' he had an idea about the wax changing into a different substance/substances. Another student, Manish asked a question 'Where does the flame go?' He continued to provide an explanation for where the flame went – 'Like the wax burns and becomes gas and mixes with the air the flame also mixes with the air'. Further conversation with Manish indicated that he thought of a flame as a specific substance. In another class, he had offered the explanation to the question 'What happens when hydrogen burns?' by saying, 'It will become hydrogen plus flame … like hydrogen plus oxygen. Hydrogen plus oxygen is water no, like that … What is it called hydrogen plus flame?'

Questions

1. What would you infer from this about Manish's ideas? How would you proceed to develop students' understanding of burning, chemical change and flames?
2. What is a flame?
3. In an earlier attempt to explain various observations related to burning, it was believed that inflammable material contained an element called phlogiston that was released on burning. This could be seen in the form of flames. Refer to the 'The Logic of Phlogiston' (https://edu.rsc.org/feature/the-logic-of-phlogiston/2000126.article?adredir=1) and explain the basis for the belief in phlogiston. What are the arguments against the existence of phlogiston?

Enact a play between two groups of chemists where one group argues in favour of phlogiston and the other argues against it.

Chemists' meanings for words 'substance', 'element', ' pure', 'reaction', 'dissolving', 'melting', etc. differ from everyday meanings. Children need to be given opportunities to learn these chemists' meanings rather than to be told the terms alone. In the inquiry-based classes conducted at the alternative school, teachers came to the following understanding which they recorded in their notes:

> In order to really help children think about everyday phenomena it seems to help if we use words from everyday language. Otherwise the tendency is for things to remain within the textbook/classroom teaching and children don't necessarily connect it with everyday events and observations.

Such reflective observations on the part of teachers would lead them to think of ways in which they can transform conceptual explanations in ways that make more tangible meanings to students. This also means that teachers should pay close attention to students' observations and explanations and deliberately hold back from offering quick formal explanations. Students, like Manish, often form their ideas by naively assimilating some of the taught concepts into their existing conceptual schemas and arriving at explanations that are at variance with the accepted scientific explanations. In the next section, we will discuss how inquiry-based teaching of chemical reactions can be taken up in order to promote better understanding among students. In the process, it is also hoped that teachers will be able to develop robust PCK of chemistry.

Teaching Chemical Reactions: An Inquiry Approach

As discussed in the first section of this chapter, the discipline of chemistry is all about understanding substances and their transformations into other substances. These transformations occur mainly through chemical reactions. Thus the study of chemical reactions is at the core of chemistry. Understanding chemical change and chemical reactions forms the basis for developing chemical knowledge. Although not exhaustive, this section will look at some areas where students have a problematic understanding with regard to chemical reactions and suggest possible inquiry-based teaching approaches.

Children will have experienced many examples of chemical change in their daily lives such as burning, rusting, fermenting and cooking without realising that all of these involve chemical reactions. It is not immediately obvious to children that new substances are produced in these processes. Because they rarely understand the concept of a substance they don't see substances being changed. Vogelezang (1987) suggests that the notion of 'substance' should be taught before teaching about atoms and molecules because this relates more closely to students' own experiences. Since students tend to think of matter as continuous rather than consisting of discrete entities or particles, the term 'substance' is closer to their notion of 'stuff' than are particle-oriented words 'atom' and 'molecule'.

The concept of 'substance' is related to other ideas like material/object, purity and chemical change. One research study (Johnson, 2002) found that 11–14-year-olds did not classify an iron nail and iron wool as 'solid', because they thought of solids as 'having no holes' or existing in 'lumps'. A chemist focuses on the material, rather than the shape, so regard both forms as 'solid'. The use of 'pure' is also problematic because in the everyday world this implies 'untampered with' or 'natural' as in the use of terms like 'pure milk' and 'pure honey'. Students are likely to think that water from a household water purifier device is purer than distilled water.

These ideas contradict the chemist's view that a pure substance comprises one single substance, rather than more than one. Thus, although using the word 'substance' may help, foundations must be laid about chemists' meanings of this term before it can be used in a strategy for teaching about chemical and physical changes (Kind, 2004).

Students frequently believe that to get something new, things just need to be mixed together (Johnson, 2002). According to several children, when a chemical reaction does take place one or other of the reactants is just modified, it hasn't really changed. For example, rust is still iron/steel, it has just gone brown. Rust flaking off is not noticed, iron just disappears. Gas bubbles that are frequently produced when a tablet dissolves in water are often not seen as a new substance. On the other hand, processes like sugar or ink mixing with water, the use of colourings in food, freezing and boiling are seen in the same way as chemical changes. When it comes to combustion, many children believe that materials like wood or paper or wax just disappear – after all there is not much of the product left to see. In burning carbon-based materials such as wood, charcoal (carbon) appears from the burning rather than the material (see Arizona State University, 2001).

Another confusion arises from the word 'chemicals'. In everyday language, the word 'chemical' typically has a negative connotation and refers to harmful substances in our food, cosmetics or other household products. Students may wrongly conclude that any and every chemical is harmful and also that these are only to be found in laboratories. In the language of chemistry, 'chemical' refers to any of the components found in various materials.

Scientifically speaking, the following key ideas are accepted in the context of chemical reactions:

- All materials are made of chemicals.
- During a chemical reaction, there is interaction between chemicals called reactants resulting in the formation of new chemicals. The properties of the new chemicals are different from those of the reactants.
  Reactants → Products
- While heat is often necessary to start reactions, this is not always the case.
- Evaporation, melting, boiling, freezing and mixing which does not result in new substances do not involve chemical reactions.
- Many chemical reactions are reversible, but in practice, they may be difficult to reverse. Changes that do not involve chemical reactions can also be difficult to reverse, for example, the grinding of grain into flour.
- Chemical reactions may proceed quickly as in the case of baking soda reacting with lemon juice to produce bubbles. Other chemical reactions like rusting can take place slowly.
- At the microscopic or particulate level, chemical reactions involve the breaking of chemical bonds in the reactant molecules (particles) and the formation of new chemical bonds between the atoms in the product. The number of atoms before and after the chemical change remains the same. The number of molecules may change as a result of a chemical reaction.
- In industries, chemical reactions are utilised to produce a wide range of useful materials; the breakdown of waste materials also involves chemical reactions that occur naturally in the environment. For some of the waste materials like plastics, there are no such reactions and they cause problems as a result because they persist in the environment for a very long time.

While teaching about chemical changes and reactions at the school level, the emphasis should be on improving student understanding and improving their recognition and understanding of what is involved in a chemical change. They should also be encouraged to understand the role played by chemical reactions in our lives and in manufacturing processes.

Inquiry-based strategies to help students learn the basic ideas discussed in this section requires teachers to avoid a traditional approach based on understanding detailed terminology and instead to present chemical events in ways which promote students to think of explanations for what they see. The first step is to help students to see that a chemical change or reaction involves the production of a new substance. Research studies show that when students see bubbles being produced when a tablet like aspirin or Eno salt is added to water they don't realise that something new is being formed. Similarly, while observing a burning candle, it is not immediately obvious to students that any new substance is being formed – unless, of course, they think of the flame itself as a substance as in the case of the student Manish, mentioned in the previous section.

Teaching activities should bring out students' existing ideas. At this stage, it is important that students are encouraged to share their ideas and discuss them in small groups. Students should be allowed to freely describe what they observe in their own words and share their ideas about what they think is causing the phenomena. At this stage, it is better not to tell students the correct scientific explanation or insist that they use proper scientific terminology. Too often teachers tend to jump in too quickly and 'correct' students' ideas.

ACTIVITY 4.4

A starting activity could be observing the burning of a candle and discussing the changes that take place. Here the distinction can be made between the melting of the wax and the appearance of new materials. Questions posed could include: What happens to the wax? What is burning? Where do you think the wax is going? Could you collect it again? Is this the same process as water evaporating? Would the candle burn if there was no air around it? Is air or part of the air used up when a candle burns?

How would you show students that new substances are produced when a candle is burning?[3]

Another interesting example of such an investigation into chemical reactions is described in de Vos and Verdonk (1985): Students grind potassium iodide and lead nitrate separately using pestles and mortars prior to tipping one solid into the other. Immediately on mixing, the powders produce a bright yellow solid (lead iodide) mixed with a white solid (potassium nitrate). The teacher fakes anger, asking, 'Who put that yellow solid in the mortar?'. This leads to indignation: 'I don't know, it just appeared', 'It came from nowhere', 'It wasn't me!' The teacher's response is 'Well it can't have just appeared, it must have come from somewhere! Where did it come from?' Eventually, students may say that the white powders are like tiny eggs, that the yellow powder was inside, so mixing them broke the 'eggs' and caused the yellow stuff to appear.

Try out the experiment described above in your laboratory and then plan how you could use it in your teaching.

Can you think of other suitable experiments that might create curiosity and get students to think about chemical reactions as involving the production of new substances?

The work of de Vos and Verdonk (1985) suggests that after helping students realise that a particular chemical reaction – like a candle burning or the mixing of potassium iodide with lead nitrate – results in the formation of a new substance in the first stage, the second stage is to help them extend their understanding to other reactions.

While teaching, through inquiry the teacher needs to set up activities which provide problems to be explored. By posing questions the teacher can challenge existing student ideas and encourage students to seek new explanations for things they observe. Students should investigate a number of changes and ask questions similar to those mentioned earlier. Students should be encouraged to observe the changes that take place and to identify what products are formed. Discussion can also centre on how these are different from the starting materials. Some examples could include:

- Baking soda and vinegar in a corked glass bottle – why does the cork fly off?
- Mixing solutions of sodium chloride and silver nitrate – will there be a change of mass when the two solutions are mixed and precipitate is formed? How can we find out?
- Pouring dilute hydrochloric acid over steel wool in a test tube – what changes are seen? How can they be explained?

De Vos and Verdonk (1985) suggest that at this stage it is possible to help students develop a particle model for the events they observe.

> A petri dish containing a thin layer of water is used initially to observe the formation of lead iodide by migration of ions. Small amounts of the lead nitrate and potassium iodide are placed at opposite sides of the dish. After a few moments, a line of crystalline yellow lead iodide appears in the centre of the dish. Students may explain this using the idea that 'molecules' of the substances 'attract' one another. This is dispelled when students repeat the experiment by adding one reactant to the dish a few minutes before the other, resulting in instant formation of the precipitate. Other combinations of substances including sugar and salt and salt and lead nitrate help students to realise that precipitates do not always form, even though 'molecules' of the substances collide with each other.
>
> *(Kind, 2004: 27)*

Following this realisation the third stage could be to help students see that heat is involved in chemical reactions.

- Mixing a solution of caustic soda with vinegar – no new substance appears to be formed, but there is an increase in temperature – why? How can this be measured and further investigated?
- When a match is lit does the heat make the reaction happen or does the reaction produce heat?

In the fourth stage students can be introduced to the idea that chemical reactions involve the rearrangement of particles. De Vos and Verdonk (1987a) note:

> Most students attribute a particular identity to a molecule and suppose the molecule keeps this identity throughout chemical reactions … According to this view … a molecule can go through many radical changes and yet retain its identity and belong to the original species.
>
> *(693)*

At this stage the students' tendency to conserve identity of substances is dealt with. The key point students need to learn is that although an atom retains its identity during a chemical reaction, a molecule does not. The authors acknowledge that changing students' thinking is difficult. Finally, de Vos and Verdonk (1987b) propose using the decomposition of malachite to introduce the idea that a 'molecule' of malachite can be 'broken' into two other substances. After this, using a copper cycle, they introduce the idea that a chemical element, copper, cannot be decomposed into anything else. Only then is the term 'atom' introduced. This sequence of steps describes a valuable way of providing visual images to help students form an accepted view of chemical changes. Students are assisted at the outset to make the physical/chemical change distinction and thereafter to realise that chemical changes occur on a microscopic scale between atoms (Kind, 2004).

As noted in an earlier section, the current set of the NCERT science textbook also introduces the notion of atoms and atomic structure at a much later stage than what used to be the practice in earlier textbook series.

SUMMARY

In this chapter, we learnt:

- The discipline of chemistry is all about understanding substances and their transformations into other substances. These transformations occur mainly through chemical reactions. Thus the study of chemical reactions is at the core of chemistry.

- The idea of an element finds its empirical base in the existence of simple substances that cannot be separated into other substances. A pure substance may or may not be decomposable into two or more simple substances. If it is not decomposable, it can be said to be an element. If a pure substance can be decomposed into simpler substances (or elements) then we term it to be a compound. There are stoichiometric and non-stoichiometric compounds.
- Modern chemistry took shape in 18th-century Europe, after a few centuries of alchemical traditions which were introduced in Europe by the Arabs. Modern chemists continue to delve into the way atoms interact with each other by forming chemical bonds of various kinds.
- Many concepts related to formal chemistry are introduced to students by the time they finish grade 10, even if the CBSE board does not have a separate examination for chemistry as a subject.
- In the inquiry-based approach, students learn to formulate ideas and explanations about specific phenomena and then carry out simple investigations to test out their ideas. In doing so they learn many scientific concepts and principles and also reasoning and procedural skills. Studies show that students are much more likely to retain concepts learnt in this manner.
- *Pedagogical chemistry knowledge (PChK)* enables teachers to create the appropriate classroom/laboratory environment, encourage student thinking and come up with the tactics that increase student understanding of the chemistry topic being taught. An inquiry approach can serve as the hook by which teachers can capture student attention and promote conceptual change in chemistry.
- While teaching about chemical changes and reactions at the school level, the emphasis should be on improving student understanding and improving their recognition and understanding of what is involved in a chemical change. They should also be encouraged to understand the role played by chemical reactions in our lives and in manufacturing processes. Inquiry-based strategies to help students learn the basic ideas discussed above require teachers to avoid a traditional approach based on understanding detailed terminology and instead to present chemical events in ways which promotes students to think of explanations for what they see.

Exercises and Practice Questions

1. Many school textbooks present the idea of subatomic particles as rigid and solid entities following fixed orbitals. Think about how a more valid (according to modern atomic theory) notion of atomic structure could be presented

in an introductory chapter for school children. Write a brief description of atomic structure for children that gives a more scientifically valid idea about it.

2. It may be useful for you as a teacher to create a ready reckoner of the various chapters related to chemistry in the NCERT science textbooks. Create your own ready reckoner like the one in Table 4.1.

   See if you can find links with chemistry concepts in other chapters in the science textbook. Make a note of these. You may want to see if there are links to chemistry concepts in the other subjects like social sciences, math or languages.

TABLE 4.1 Grade-Wise Syllabus for Chemistry

Grade	*Chapter no. and name*	*Key concepts*	*Suggested inquiry*
6	Chapter 4: Sorting Materials into Groups	Observable properties of materials Materials and objects Soluble and insoluble	What accounts for differences in properties of different materials? How do we know if an object is made of one material or different materials?

Source: Author.

3. How would you justify delaying the introduction of atomic structure and valency to a later stage based on research into students' understanding of chemical concepts?
4. Construct an inquiry-based teaching plan for chemical change following these steps:
   - Decide on the key concepts that you want students to understand.
   - Read about some common conceptions that students may have about the above.
5. Interview three to four students to find out their conception about the topic.
   - Plan the inquiry experience for students and decide how you will note their questions and help them with the experiments and build understanding.
   - Construct an evaluation rubric/plan to check for student understanding.

Notes

1 Allotrope: 'The term allotrope refers to one or more forms of a chemical element that occur in the same physical state. The different forms arise from the different ways atoms may be bonded together. The concept of allotropes was proposed by Swedish scientist Jons Jakob Berzelius in 1841. The ability for elements to exist in this way is called allotropism. Allotropes may display very different chemical and

physical properties. For example, graphite and diamond are both allotropes of carbon that occur in the solid state. Graphite is soft, while diamond is extremely hard. Allotropes of phosphorus display different colors, such as red, yellow, and white. Elements may change allotropes in response to changes in pressure, temperature, and exposure to light' (https://www.thoughtco.com/allotrope-definition-in-chemistry-606370).

- Non-stoichiometric compounds: These are compounds whose elemental composition cannot be represented by a well-defined ratio of natural numbers. Such compounds do not follow the law of constant proportions. Examples of non-stoichiometric compounds include transition metal oxides, but also fluorides, hydrides, carbides, nitrides, sulfides, tellurides, and so on (from *Modern Inorganic Synthetic Chemistry*, 2nd Edition, 2017).
- Inclusion compound: A complex in which one component (the host) forms a cavity or, in the case of a crystal, a crystal lattice containing spaces in the shape of long tunnels or channels in which molecular entities of a second chemical species (the guest) are located.

2 Iatrochemistry is a branch of both chemistry and medicine. Having its roots in alchemy, iatrochemistry seeks to provide chemical solutions to diseases and medical ailments.

3 Faraday's famous Christmas lectures about candle burning provide fascinating scientific explanations. Refer to http://engineerguy.com/faraday/ and http://www.arvindguptatoys.com/arvindgupta/vp--faraday-candle.pdf

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5

A SOCIO-CULTURAL APPROACH TO LEARNING BIOLOGY

> We are the product of 4.5 billion years of fortuitous, slow biological evolution. There is no reason to think that the evolutionary process has stopped. Man is a transitional animal. He is not the climax of creation.
>
> – Carl Sagan

In this chapter, we will study the socio-cultural approach and various pedagogic practices influenced by it. We will learn in detail about a pedagogic approach called the history and philosophy of science (HPS) and we will take the example of evolution as an exemplar topic to see how the HPS approach can be used to teach evolution. We learnt a little bit about the history and philosophy of science in Chapter 1. In the HPS approach, while teaching a topic, historical development of that topic is used as a resource. In the following sections we will see how it is done.

OBJECTIVES

The objectives of this chapter are to help you:

- take a closer look at biology and its characteristics.
- learn about the socio-cultural approach to science education.
- learn about the history and philosophy of science approach to teach the theory of evolution as an example of the socio-cultural approach.
- look at common alternative conceptions about the theory of evolution and ways by which those alternative conceptions can be cleared.

DOI: 10.4324/9781003047506-6

We will begin with a study of the characteristics of biology as a subject and see what makes it different from other subjects and why unique features of biology should be kept in mind while learning about pedagogic interventions for topics in biology. Then we will look at some common alternative conceptions about evolution students and teachers across the world have. Finally, we will see how the HPS approach can be applied in teaching the topic of evolution. This chapter is organised as follows:

- What Is Biology?
  - Scope of Biology
  - Characteristics of Biology
- Biology as a School Subject
- Socio-cultural Approach in Science Education
  - Pedagogic Approaches Influenced by the Socio-cultural Approach
- Exemplar Topic: Theory of Evolution
  - Some Common Alternative Conceptions About Evolution
  - Addressing Alternative Conceptions About Evolution with History and Philosophy of Science
  - Supporting Learning with Digital Activity
- Summary

What Is Biology?

Human beings were always curious about living things around them. Curiosity-driven observations led to the domestication of animals and plants and the formulation of medicines to heal wounds. Of course, the observations and experiments by early humans were not called 'biology'. The term is recent; it was coined in the 18th century (Mclaughlin, 2002). Biology means the study (*logia*) of life (*bios*). That is the time when the systematic study of living organisms started and it gave birth to the modern biological sciences. Until then it was believed that life arose from dead matter like mold growing on food, or that animals did not evolve. In the 17th century, the invention of microscopes changed the old notions. We learnt that organisms are made up of tiny cells which are the basic functional unit. And cells do not automatically spring to life, they come from pre-existing cells, which means life can only arise from pre-existing life. This notion collectively called cell theory became one of the cornerstones of modern biology. Biologists wondered how organisms change, how life on earth is so diversified and where humans come from. The ground-breaking work of Lamarck, Darwin and Wallace showed that life changes over time, the changes accumulate and eventually give rise to new life forms or species. Changes that are passed from generation to generation are selected by nature and characteristics that help organisms to survive get propagated, while others vanish from the population. The theory proposed by Darwin and Wallace was called the theory of evolution by natural selection, and it became another cornerstone of modern biology. Darwin and Mendel did not know about DNA or genes but they postulated that characters are passed from one generation to another, and Mendel gave the rules of such inheritance. After Rosalind Franklin, Watson and Crick discovered the structure of DNA, we learnt that cells have chromosomes and chromosomes have bundled DNA. The DNA contains genes that have information to synthesise proteins. Proteins play various roles in organisms. The new field which studies DNA, genes, their structure and function is called genetics. It is another important cornerstone of modern biology (Figure 5.1).

FIGURE 5.1 Nature and nurture, inextricably intertwined. Source: Illustration by Karen Haydock.

Scope of Biology

Modern biology studies various aspects of life such as the evolution of living organisms, their structural organisation, chemical and molecular interactions, physiological mechanisms and the development of organisms. Biology is concerned with the systematic study of life on earth or anywhere in the universe. It covers a range of questions like what life is and how it originated, at one end, to whether there is life on other planets, at the other. Biology has many branches such as botany, zoology, microbiology, etc. These branches are decided based on the subject matter of their investigations. Botany studies plants, zoology studies animals, whereas microbiology studies organisms that are extremely small and can't be seen with naked eyes. Along with these three important branches, there are a few others that are decided based on what aspect of living organisms they study. For example, branch ecology is concerned with how organisms are distributed at different places and how the distribution changes over time. It also studies what causes the change in the distribution of organisms and what its consequences are. Similarly, each branch of biology focuses on some specific aspect of life. Here are some common branches of biology: Taxonomy, morphology, anatomy, histology, cytology, cell biology, physiology, embryology, ecology, genetics, evolution, palaeontology, exobiology and virology.

ACTIVITY 5.1

In the aforementioned branches of biology, are there any new names that you were not aware of? Find out the topic of study of all the branches just mentioned.

Characteristics of Biology

Biology has certain characteristics that make it different from the physical sciences (physics and chemistry). The object of study in biology is life and life is extremely complex. To put it in Ernest Mayr's (2004) words, 'there are no inanimate systems in the mesocosmos that are even anywhere near as complex as the biological systems of the macromolecules and cells'. The complexity and openness of biological systems make the study of it with only a reductionist approach futile; a holistic approach is needed.

Evolution is another idea that makes biology distinct from physics or chemistry. In physical sciences, we do have branches such as cosmology and geology that study the evolution of the universe or earth but in biological sciences, evolution is the central idea. Everything in the living world is understood with the help of evolution. The driving force of evolution is natural selection, specifically organic evolution, and there is no phenomenon equivalent to it in non-living matter.

Another difference between biological science and physical sciences is that the biological processes are subject to 'dual causation' (Mayr, 2004). Here dual causation means two sets of factors controlling the processes; the first one is natural laws and the second one is genetics. There is nothing like this in physical sciences; everything is explained using natural laws. But in the biological world, all the life forms are partly controlled by genetics and partly by natural laws. And it makes biology, the study of such objects, unique in some sense.

Physical (natural) laws such as laws of motion generally have deterministic outcomes, but in the biological world, such deterministic outcomes are rare. Both natural selection and sexual selection make it difficult to determine a specific outcome. Any outcome is the result of the interaction of many incidental factors which brings aspects of chance into the picture. For example, dinosaurs were best suited to survive till an asteroid completely changed the environment and it became impossible for many dinosaurs to stay alive. The random (chance) event played an important role in selecting out most of the dinosaurs from the earth.

These are some of the aspects of the living world that makes biology different from other sciences. It is important that when we teach biology in school, we make sure that students should also understand these characteristics of biology as a subject. In the next section, we will see why should include biology as a school subject and how we should teach it.

Biology as a School Subject

Like physics and chemistry, biology is also taught at the school level in India and across the world. The reason for including it as a subject is multifold. It is taught because the subject of study in biology is living things and students are surrounded by living organisms. Children are curious and it is natural for them to have questions about living things they see around them including their own bodies. Studying biology can help them understand their bodies and different aspects related to health and hygiene. Learning about the living world can help them understand the complex nature of the living world and their connection to it. Distinct characteristics of biology can help students develop ideas and skills that are not there in other subjects. They can learn about ideas such as evolution, natural selection, growth and development, interconnectedness and classification, diversity, etc. The study of biology can also help students develop skills such as observing, surveying, sampling, monitoring and classifying.

In the next section, we will look at common approaches to teaching biology at the school level.

Further Reading

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Socio-cultural Approach in Science Education

In Chapter 1 we learnt that there are two prominent approaches, namely cognitive and socio-cultural. While in Chapter 3 we learnt about the cognitive approach, here we will look at the socio-cultural approach. The socio-cultural approach is an amalgamation of development in two different areas of research; one is investigation of the nature of learning and the other one is the study of nature of science.

People such as Piaget, who studied learning and development, took the cognitive approach (discussed in Chapter 3), and were criticised by Bruner and others for not giving enough importance to social interaction in learning and development. The cognitive approach was challenged by people like Vygotsky who pointed out the cultural origin of a child's understanding of language, cultural symbols and logic. Children learn from peers who are more experienced and such social interactions play an important role in cognitive development.

Around the same time, many working on the history of science, sociology of science and cultural anthropology were challenging the rigid view of science. The view was that the scientific approach to knowledge is not affected by social and cultural beliefs, politics and social institutions. The work of people like Shapin, Schaffer, Latour, Hutchins and Haraway was instrumental in creating a view where science is seen as a human activity. And like all other human activities science is also affected by dominant political and cultural beliefs at any given time in history. For example, many feminist scholars have pointed out that in the past women and women's issues did not find a place in science (Longino & Hammonds, 1990). It was a direct effect of the male-dominated culture of that time. As the culture changed, more and more women entered the workplace and in science. With more women doing science, women's issues also started finding a place in mainstream science. It shows how culture and politics shape science. The work of Hutchins and others expanded the notion of the cognitive system; they included tools and artefacts along with the individual and its social environment. Instruments and technologies are integral to science; they support cognition and make new knowledge possible.

Pedagogic Approaches Influenced by the Socio-cultural Approach

Learning theories have a direct influence on the pedagogies used by educators. In Chapter 3 we learnt about some pedagogies influenced by a cognitivist approach. Here we will look at how socio-cultural approaches have shaped various pedagogic practices. Project-based learning (PBL), (authentic) activity-based learning, collaborative learning, computer-supported collaborative learning and the history and philosophy of science approach are some examples of pedagogies that are influenced by this approach. In this chapter, we won't be studying all these approaches in detail, but we will choose a few and explain them in detail in the following sections. Socio-scientific issues provide a good starting point to bring in pedagogic practices based on the socio-cultural approach.

Socio-scientific Issues in Science Curriculum

Socio-scientific issues (SSI) are controversial social issues that are related to science and technology (Raveendran, 2021). They are poorly structured and have multiple solutions. Genetically engineered food, use of animals in medical testing, climate change and commercial surrogacy are a few examples of SSIs. These are open-ended issues that are being debated by society at large. Educators and proponents of critical science education argue that science textbooks should include socio-scientific issues. Students should be exposed to issues that are open-ended and that require logical, ethical and moral reasoning.

To understand the idea of socio-scientific issues better, an example would help. We will look at the work of Raveendran (2021), who is a researcher from India. In one of her studies, she introduced the issue of commercial surrogacy to school students and analysed how students engage with the issue. She chose commercial surrogacy as an exemplar issue as students have some exposure to it through popular media such as television, newspapers and the internet. Commercial surrogacy in simple words is an arrangement where an individual (or couple) who is not carrying the pregnancy in her womb due to some reasons, selects a third person (a female) to undergo in-vitro fertilisation (IVF) and carry the baby till birth. The third person called the surrogate mother agrees to carry the pregnancy for various reasons, financial being the most prominent reason. The countries where IVF is unregulated attract wealthy people from other countries who look for commercial surrogate mothers to raise their children. Commercial surrogacy is considered a socio-scientific issue because the issue is open-ended and it has many dimensions. Raveendran points out that commercial surrogacy is a high-profit industry and poor and distressed females agree to become surrogate mothers due to the money they will be getting out of it. But the IVF procedure involves health risks for both the surrogate and biological mothers. Indian surrogate mothers face risk as they are malnourished due to poverty, have already had children of their own and additional pregnancy puts extra strain on their bodies. IVF also involves the transfer of multiple foetuses into their wombs to ensure pregnancy and the use of various medicines to induce pregnancy. Both these things put surrogate mothers' health at risk. Even though these risks may be public knowledge, surrogate mothers may not be competent to understand them due to illiteracy or no scientific knowledge. When Raveendran presented the topic of commercial surrogacy to students from Indian schools, she found that even though students pointed out many social and ethical concerns, they struggled to understand many complex issues concerning political, economical and social dimensions of the issue. For example, students failed to understand the nature of poverty, they felt that the money coming from commercial surrogacy will help the surrogate mothers come out of poverty. Students were not able to realise that the money surrogate mothers get is not enough to make any long-term change in their lives. Involvement of money makes poor women rent their wombs for the wealthy and reap benefits of social inequalities with technology like IVF at considerable costs to their health. Raveendran's study pointed out the need for students to engage more effectively and sensitively with SSIs and the necessity for science education to impart the necessary skills to do so. The science curriculum needs to include SSIs in textbooks. Teacher education also needs to prepare teachers to engage these multifaceted issues so that they can have a discussion around these issues in their classrooms using a politicised perspective.

Collaborative Learning

In a socio-cultural approach, learning is considered fundamentally a social activity. Naturally, any pedagogical approach where social interaction is central will also be suitable for learning. In a collaborative learning approach, learners are not only interacting with each other but also playing an active role in each other's learning process. In traditional classrooms the interaction is limited to student and teacher; rarely do students get to interact with each other, which suggests that the students can only learn from the teacher and not each other. But in a collaborative learning approach, the entire group or class learns together. Vygotsky's idea of the zone of proximal development (ZPD) explains how students can learn from each other. A student can move from one level to another with the help of any 'knowledgeable other'; it doesn't have to be only a teacher or an adult, it can be another student in the classroom who has understood the concept. In this approach the teacher is no longer the only source of knowledge, therefore the role of the teacher in the learning process is changed. The teacher plays the role of a facilitator who makes sure that the students are interacting with each other, every student is participating in the group activity and keeps the group activity on track.

In a collaborative learning approach, if the number of students in the classroom is more, the teacher can divide the students into small manageable groups. Students work in small groups and at the end of the activity rejoin the entire class in sharing their work. To ensure that all students get equal opportunities to learn, teachers have to make sure that the group composition is such that no one student dominates the group or no student is left out. To ensure this teachers can choose any strategy from multiple strategies suggested by the educators, teachers and practising teachers.

Computer-Supported Collaborative Learning (CSCL)

The advent of networked computers has made new learning environments possible. One of such approaches is computer-supported collaborative learning (CSCL), where the collaboration is mediated through networked computers. Proponents of the CSCL approach argue that the computer's support has many advantages. First, it blurs the boundaries of space and time between the learners, which means the learners who are not seated in the same classroom can collaborate with each other. Also, the learners that are not in the same time zone can also collaborate with each other; for example, using asynchronous discussion forums like modules, a learner can post a comment and a few hours later another learner from a different country can respond to it. Second, interactions in CSCL settings can be saved and can be accessed anytime. Such an archive acts as a scaffold; any learner when faced with difficulties can either reach out to knowledgeable peers or teachers or can look for any previous post that can help solve the problem (Dhakulkar et al., 2018).

Computer support can be given to both face-to-face and virtual collaboration. There is a big community of researchers who study learning in the CSCL setting and few studies have been done in the Indian context. For example, in the Connected Learning Initiative (CLIx) project of the Tata Institute of Social Sciences, a platform and modules were designed that enabled and promoted collaborative learning with locally networked computer support. A study showed that the platform helped students collaborate with peers and it improved the quality of learning. This study focused on the module on basic astronomical phenomena. Students who used the CLIx platform and module performed better than the students who learnt through the traditional method (Shaikh et al., 2018, 2020; Padalkar et al., 2020).

History and Philosophy of Science Approach (HPS)

In Chapter 2, we learnt about the nature of science and how science is a human activity. Human beings and their work are products of social, cultural and historical factors. Studying the historical development of science and various concepts in science can tell us what science is and how it works. There are many examples in the history of science that show us how dominant political, religious and ideological beliefs of the time have affected science. For example, in the early and middle 18th century, Americans were fighting with the British to get independence. Benjamin Franklin, a colonial who was politically and ideologically at war with Britain, saw the concept of electricity as a way of making a statement. At that time many British were working on understanding electricity but were struggling. Benjamin Franklin saw it as an opportunity to dispel myths around electricity and show that something that elite masters (the British) couldn't understand was explained by a colonial (an American). He suggested that the electricity generated by humans and lightning, which was considered magical, are one and the same. To prove his assertion he proposed an experiment, the famous kite experiment. But he never conducted the kite experiment; it was more of a thought experiment, as performing such an act would have killed him instantly. But he did propose another doable experiment, which was conducted not by him but by a Frenchman, which proved that lightning and electricity are the same. This example shows how the understanding of electricity is entangled with socio-political happenings of the time. For Benjamin Franklin, explaining lightning was as political as it was scientific.

When we use the HPS approach, we want students to not only learn scientific concepts better but also learn how we arrived at our current understanding of those concepts. When students learn about the history of certain concepts, we want them to also understand the nature of science through many such stories. To understand how a pedagogic approach influenced by socio-cultural approach is implemented, in the following sections, we will take one exemplar topic and explain how the HPS approach can be used in teaching and learning it.

Further Reading

Matthews, M. R. (2014). *Science teaching: The contribution of history and philosophy of science*. Routledge.

Exemplar Topic: Theory of Evolution

The theory of evolution is considered central to biology; it is a theory that helps understand almost everything related to life. Without the theory of evolution, all you have is a collection of facts. These facts don't make sense; it is difficult to understand why some organism is living in a specific niche or why some animals have body parts that do not appear to have any function. For example, it doesn't make sense that human embryos have gill slits. Gill slits help fish breathe underwater; human beings are terrestrial animals. Why do human beings have an organ which aquatic animals need? Another structure is a tailbone in human beings. Animals who walk on four legs have a tail which helps in balancing. The list of such structures is not limited to these two examples; not just the animal but the plant kingdom is full of examples of vestigial[1] structures. Only when one looks at these collections of facts in light of evolution does the idea that all life on earth evolved from a common ancestor makes sense. Organisms change over time and when changes become so big that they can no longer interbreed they become two different organisms. Various environmental factors act as selection factors. Organisms with features favourable in a given environment have more offspring and over many generations only organisms with those features survive and others go extinct. The existence of vestigial structures in organisms makes sense when we look at them in light of evolution. Human beings have a tailbone because thousands of generations back they had an ancestor which walked on four legs. It is a remnant of the tail which the human ancestor once had. The reason why it exists in modern humans, even though in reduced form, is because there was no selection pressure that might select against it. Human beings with reduced tailbone are surviving and reproducing successfully. It doesn't mean that it will always stay in reduced form. Some selection pressure in future might make humans lose it completely or bring it back to the functional tail. Evolution gives meaning to the collection of facts, it makes possible broader meaning-making from seemingly unrelated facts (Dobzhansky, 1973).

Some Common Alternative Conceptions about Evolution

Across the world, students find it difficult to understand the theory of evolution, and not just students but the general population has many alternative conceptions about evolution. Given the importance of the theory of evolution in understanding biology, we must be aware of common alternative conceptions so that we can make sure that we address them while teaching evolution in classrooms.

1. It is commonly believed that evolution is a process in which only the strongest or fittest organisms survive and the weak ones go extinct. This alternative conception has roots in faulty understanding and use of the phrase 'survival of the fittest'. It gives the impression that the organisms who are strong survive, which is incorrect; organisms who are best suited for given environmental conditions survive and reproduce. For example, around 65 million years ago, due to volcanism and asteroid impact, the climate changed and the mighty dinosaurs couldn't survive and went extinct, whereas tiny little animals who could burrow into the soil survived.
2. Students believe that the theory of evolution is all about human evolution and that humans evolved from apes. Both these notions are incorrect. The theory of evolution is a grand theory that explains how all living organisms

change in response to the environment over many generations. The changes accumulate over time and give rise to new life forms or species. And human evolution is just one case. The idea that humans evolved from apes is displeasing to many even though it is incorrect. Humans did not evolve from apes; we had common ancestors. This means if you go back many many generations there was a population which was the great- … great-grandparents of both humans and apes.

3. The most common alternative conception is that organisms change throughout life to cope with changes in the environment. Students think organisms undergo change like a metamorphosis of an egg into a larva and then into a butterfly. Organisms do not evolve during a lifetime, evolution happens at a population level and over many generations. The diagrams (Figure 5.2) which are used in many textbooks also contribute to this alternative conception. They give the impression that individuals change into better individuals.
4. Another common alternative conception is that the theory of evolution is just a theory, meaning just a guess. People think it is not a fact or law like Newton's laws of motion. The root of this alternative conception is poor or no understanding of how science works. As discussed in Chapter 2, in science the word theory has a specific meaning and it is different from the colloquial meaning. In science, law and theory are not interchangeable and one is not superior to another. A scientific theory is not just a guess, it is a carefully crafted explanation that undergoes extensive scrutiny by scientists. The theory of evolution has survived the test of time and that is why it is much more than just a guess.

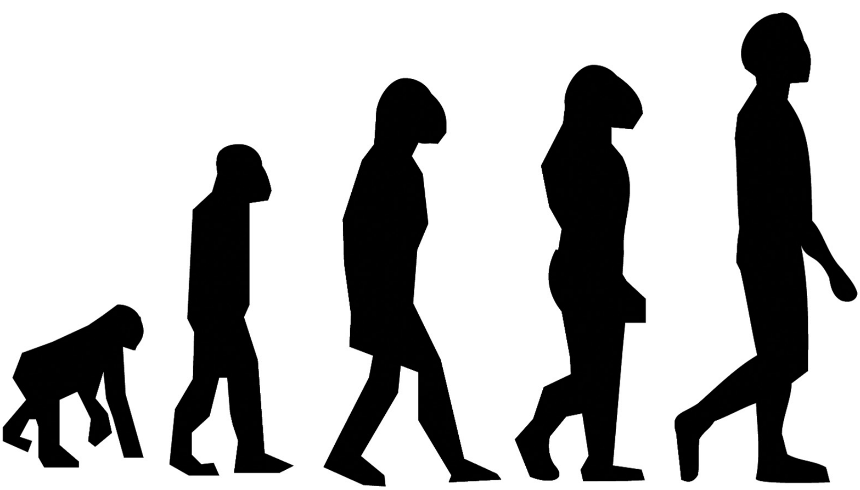

FIGURE 5.2 A commonly used but incorrect depiction of evolution. Source: Wikimedia Commons.

Some of the alternative conceptions of students on evolution, in fact, mirror the historical development of ideas on evolution (Monk & Osborne, 1997).

> **ACTIVITY 5.2**
>
> Did you have any of the alternative conceptions about evolution mentioned in this chapter? If yes, what was it and why might it have got created in the first place? Did you know any alternative conceptions that were not mentioned in this chapter?

Addressing Alternative Conceptions about Evolution with History and Philosophy of Science

Human beings have always been curious about their origins. Almost every culture has some creation myth or origin stories that describe how the universe came into existence, how humans and other living things got created. Most of the stories believed that once living things got created, they remained unchanged.

> **ACTIVITY 5.3**
>
> What is the creation story in your local culture? And how is it different/similar from those of other cultures?

After the scientific revolution, it was only natural that humans again asked the same question. The first notable person to study the changes in organisms over time was Jean-Baptiste Lamarck (1744–1829). By then scientists knew that organisms change (evolve) over time but how that happens was a mystery. Lamarck was the first one to propose a mechanism for evolution. He proposed that simple changes that happen during the lifetime of an organism are inherited by its offspring; these changes add over time and new species are evolved. The changes happen as a result of organisms trying to improve themselves. For example, he said giraffes have long necks because their ancestors stretched their necks to eat leaves on tall trees. When a giraffe's neck gets a little long due to stretching, its offspring are born with long necks. Over many generations, the neck got longer and longer and it became today's giraffes. The mechanism has two main aspects. First, the organism acquires changes as a result of its interaction with the environment. And second, the acquired change is passed on to the next generation.

ACTIVITY 5.4

Find out whether traits such as skill in playing the violin or javelin throwing are inherited.

The second notable person to propose the mechanism of evolution was Charles Darwin, but he was not alone; simultaneously Alfred Wallace came up with the same idea. In 1858, they jointly proposed the mechanism of evolution. They called it evolution by natural selection. Both Darwin and Wallace were naturalists and had travelled extensively. They built their theory on the observations made during their travels. Charles Darwin got an opportunity to visit many places and observe the diversity of life. He was the naturalist who was tasked with documenting the natural history of the places the HMS *Beagle* ship visited. During his voyage, Darwin collected many fossils, specimens and recorded notes. The most important part of his trip turned out to be the visit to Galapagos Islands. These are a collection of many tiny islands. At the time he visited, he didn't realise its importance, as he was just a young naturalist observing and collecting whatever he could. But later, while analysing his collection, Darwin noticed that all the different birds he had collected from different islands were different kinds of finches. The second thing he noticed was that the shape and size of the beaks were specific to the island they came from. This made Darwin think that all the finches must have had a common ancestor. Sometime in the past, a population of finches must have arrived at these islands and over the course of time changed into different varieties of finches, Darwin thought. He also observed a variety of tortoises on the Galapagos Islands. The tortoises from each island were slightly different, their shell size and shape, neck size, etc. varied. Darwin learnt that the locals could just look at a tortoise and guess the island it belongs to. This too made Darwin think that all the tortoises must have had a common ancestor. But the question was how did that original population change? Darwin used his observations from two unrelated fields. During Darwin's time, it was known that features on earth such as valleys and mountains undergo a change over time. Simple geological processes can create huge changes over extremely long periods of time. The second observation was of domesticated dogs. In the Victorian era, people were fond of dogs and dog breeders had artificially created various breeds of dogs by careful breeding and selection. Breeders were artificially selecting one feature (height or fur or colour, etc.) over others and creating new breeds of dogs. Darwin thought something similar must have been happening in finches and tortoises in the Galapagos Islands. There instead of human agents selecting artificially, nature was selecting. He called it natural selection. He explained the observations from the Galapagos Islands using natural selection. The Galapagos Islands are not very old; they got created due to volcanic activity in the recent past. When the islands became habitable a population of land finches (Figure 5.3)

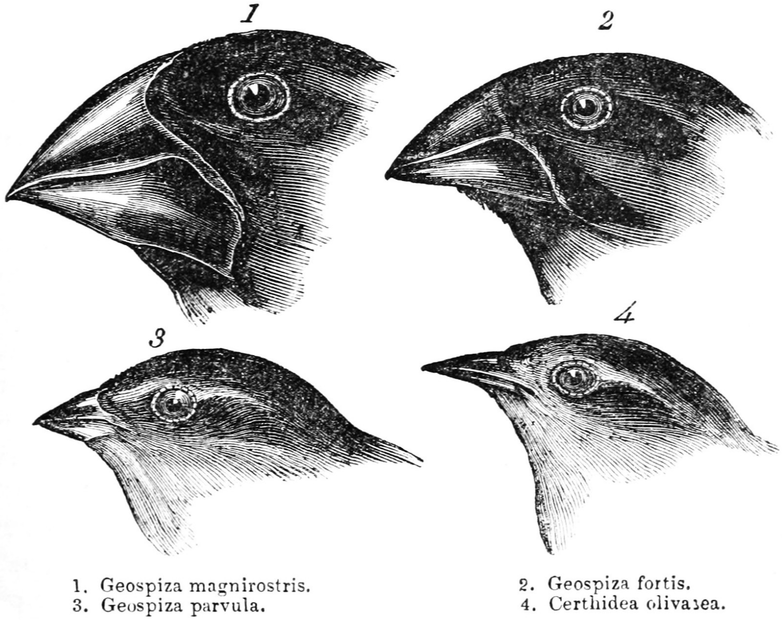

FIGURE 5.3 Darwin's finches by Gould. Source: John Gould, from *Voyage of the Beagle*, Wikimedia Commons (https://upload.wikimedia.org/wikipedia/commons/a/ae/Darwin%27s_finches_by_Gould.jpg).

reached the group of islands. Each island has a different soil composition which supports specific flora. The finches mostly eat seeds. The type of seeds present on the island acted as a selection pressure. For example, the island which had hard seeds selected finches which have small but sturdy beaks. The original population of finches must have had natural variations and the ones with little sturdy beaks fared better than others on islands with hard seeds. Their offspring had sturdy beaks and in turn, they survived and reproduced better than the others, and over many generations, the island was dominated by the finches with small and sturdy beaks. Similar selection pressures on other islands led to finches on that island having beaks of different sizes and shapes. Similarly, Darwin also explained how differences in the ecology of each island acted as a selection pressure for tortoises and resulted in having tortoises with unique characteristics on each island. Darwin took time to formulate and refine his ideas; he was reluctant to publish his work, thinking it might create controversy as his ideas were different from the prevalent religious notion of the time. But when Darwin came to know that Alfred Wallace had come up with a similar idea on his own, Darwin's friend urged him to publish his work immediately. Darwin published his seminal work *On the Origin of Species* in 1859. In later years, Darwin's theory became popular and received positive feedback from fellow scientists.

Despite being revolutionary, Darwin's theory of evolution was not complete. It had gaps, for example it says that organisms evolve over time but it does not explain the mechanism of evolution. It took another discovery to fill the gaps in Darwin's theory. In 1953, James Watson, Francis Crick, Maurice Wilkins and Rosalind Franklin discovered the structure of DNA. It opened a completely new world of possibilities. Scientists found that DNA can carry biological information from one generation to another. Each cell has a nucleus where most of the DNA is stored. The DNA (or RNA) has biological information in the form of a code made up of just four letters (nucleotides). Series of nucleotides form a gene which is a functional unit of genetic information. Each gene contains information to synthesise a unique protein molecule. The protein molecules are the building blocks of cells and control various characteristics of the organism. Scientists found that the sequence of nucleotides changes due to various reasons such as radiation, recombination or during replication. Sometimes mistakes happen in the copying of the sequence of the nucleotides in new DNA (or RNA) molecules too. The change can either make the gene dysfunctional or it can be neutral, meaning it doesn't have any effect on the function of the gene. In some cases, the change creates a new gene which performs new functions or has new characteristics. If the new characteristics give some advantage to the organism in the given environment, it reproduces more than other individuals in the population, and over many generations, the number of individuals with new genes increases compared to individuals without new genes. When many such changes accumulate in a large group of individuals there comes a time when they cannot reproduce with the parent population. That is when we say a new species has been formed. The field of biology which studies genes is called genetics and it filled many gaps in Darwin–Wallace's theory of evolution. The resultant theory is called neo-Darwinism.

Supporting Learning with Digital Activity

Evolution is an extremely slow process which takes hundreds or thousands of years to take place and it works at the population level and not at the individual level. These two aspects make it very difficult to show evolution at work to students. In the absence of it, like scientists, students also have to look at fossil records, anatomical features, etc. and draw inferences about what might have happened. New technology offers some hope here. New media tools such as simulations, animations, videos and models can show how evolution works. We can artificially control the population size, generation times, traits, etc. and simulate the evolution process in the wild. Speeding up the simulations, animations make extremely slow evolutionary change visible to students which in turn can help students in understanding the concept of evolution.

Here we take an example of a simulation from a group called NetLogo, and demonstrate how such a simulation can be used in teaching evolution to students.

The simulation is of peppered moths (Wilensky, 1997) and their colour changes. Since Darwin proposed the theory of evolution, there was no example of evolution in action. This was the first good example where evolution taking place can be seen. The simulation is interactive and gives students the opportunity to visualise the change in peppered moths (Figure 5.4) over years and the effect of various factors on it.

To view the simulation, open the link in the browser of your computer or phone. At the bottom of the page, you'll see three tabs: command centre, NetLogo code and model info. Click on the model info tab, it will expand and you will see detailed information about the model. The model info section describes what this model is about, how it works, how to use it, what are the things you should notice while using the model what are the things you should

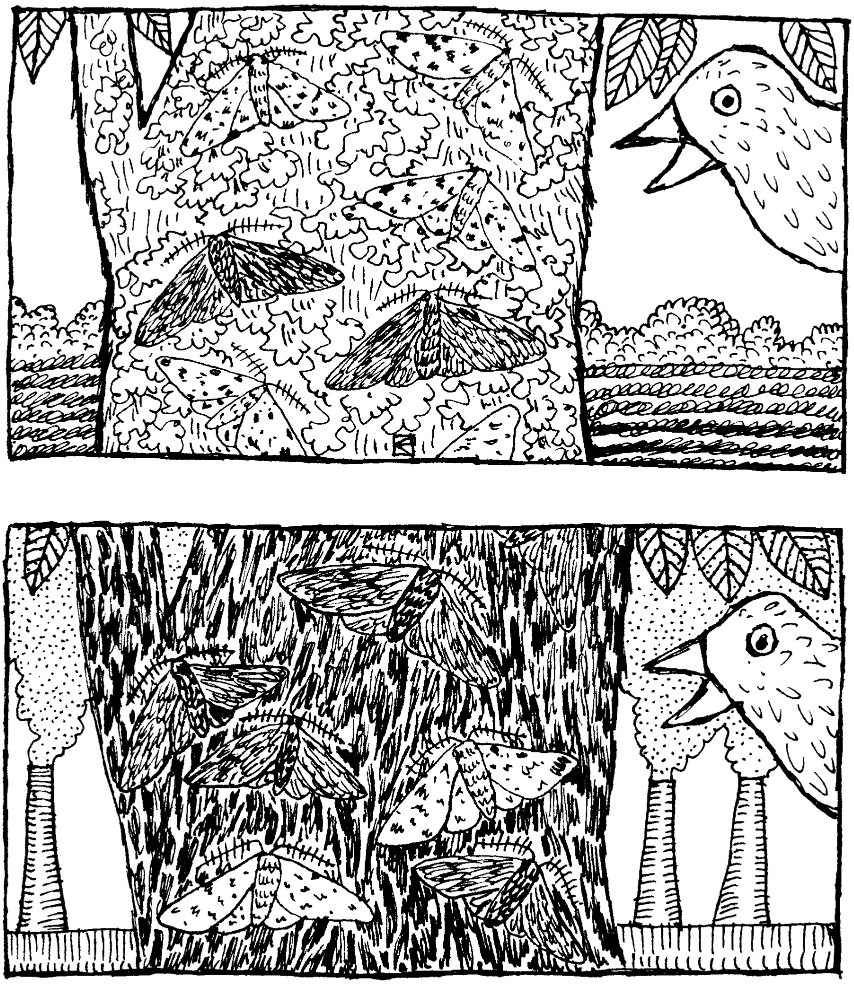

FIGURE 5.4 Artistic drawing showing evolution of peppered moths. Source: Illustration by Karen Haydock.

try and finally how you can extend this model to other related topics. Read the information carefully and try out the model. While trying out the model you should take notes and think about how you can incorporate this simulation in your lesson plan while teaching evolution in the classroom.

ACTIVITY 5.5

Explore various OERs (open educational resources) and find out if they are effective in correcting the alternative conceptions.

For example, a simulation showing the evolution of mimicry in organisms:

http://netlogoweb.org/launch#http://netlogoweb.org/assets/modelslib/Sample%20Models/Biology/Evolution/Mimicry.nlogo

Further Readings

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SUMMARY

In this chapter, we learnt:

- Biology studies life including its origin, development and evolution.
- Biology is similar to other sciences but has its uniqueness.
- Socio-cultural approach as opposed to the cognitive approach is an amalgamation of insights from the study of learning and the study of nature of science.
- All sciences including biology have socio-cultural origins and are affected by social, political, economical and cultural factors.
- Social interactions are vital for learning; pedagogic practices that involve social interactions are better for learning science.
- Theory of evolution is central to biology and biology cannot be understood without it.
- Students across the world struggle to understand the theory of evolution and carry many common alternative conceptions such as that

evolution happens at the individual level or that evolutionary change is like the metamorphosis of butterflies which happens during the lifetime of an organism.

- Various pedagogical approaches can be used in teaching the theory of evolution. In this chapter we looked at the HPS approach and use of new media as a support for teaching evolution.
- In the HPS approach, the teacher uses the history of the theory of evolution – how the theory started and how it developed over time. The purpose of using titbits from the history of the development of the theory is to use these cases to show that the common alternative conceptions existed in the past and why our understanding moved from those concepts to the current accepted concepts.
- In the HPS approach, teachers use examples from the past as some of them mirror the common alternative conceptions and then present a counter-argument to achieve conceptual change.
- New media tools such as simulations, animations, videos and models can also be used in teaching the theory of evolution and achieving conceptual change.

The peppered moth model on the NetLogo platform is a good example of how such simulations can help students in visualising processes like evolution which are extremely slow, take hundreds and thousands of years to take place and happen at the population level which makes them almost impossible to observe.

Exercises and Practice Questions

1. Design a lesson for a topic of your choice using the HPS approach and try it with a few students.
2. We learnt about the socio-cultural approach in this chapter; design a lesson plan to explain it to a few students. Use examples/cases which are either familiar or relatable to students.
3. Choose a topic, find a few students and interview them. Through the interview try to understand the alternative conceptions students have about that topic.
4. Use the list of alternative conceptions obtained from the aforementioned activities. Design an activity/lesson to teach that topic in a way that helps students correct alternative conceptions.
5. What are the advantages and disadvantages of new media (information and communication technology) and what type of concepts can be taught using new media? Think of a concept, find a new media OER for it and try it out with your students.

6. Go to OER repositories like PhET Simulations, NetLogo or CLIxOER. Use the six-point criteria given on the COOL-OER page of the Tata Institute of Social Sciences to select an OER. Try out the selected OER with a few students.

Note

1 Vestigial is meant (of an organ or part of the body) as degenerate, rudimentary or atrophied, having become functionless over the course of evolution.

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6

ASSESSMENT IN SCIENCE EDUCATION

ὁ δὲ ἀνεξέταστος βίος οὐ βιωτὸς ἀνθρώπῳ – Σωκράτης	An unexamined life is not worth living. – Socrates

Students often hate examinations, yet they study to pass examinations. What teachers choose to teach and what students choose to learn largely depend upon the kind of assessment students will be expected to undergo. Examination is only one kind of assessment. What other kinds of assessments are possible? In this chapter, we will take a careful look at the practice of assessment and discuss how assessment can be made less threatening yet more beneficial to everyone.

OBJECTIVES

The objectives of this chapter are to help you:

- understand what assessment is and what purposes it serves.
- discuss different types of assessment (diagnostic, formative, summative, large-scale learning assessment [LSLA]).
- design assessments and rubrics to evaluate students' responses.
- deliberate upon principles of providing feedback.

The chapter is organised as follows:

- Assessment and Evaluation

DOI: 10.4324/9781003047506-7

- Purpose of Assessment
  - Screening and Selection
  - Assessment of Learning
  - Assessment for Learning
  - Assessment as Learning
- Assessment in Science Education
  - Diagnostic Assessment
  - Formative Assessment
  - Summative Assessment
  - Large-Scale Learning Assessment
- Ensuring Quality of Assessment
- Peer Assessment and Self-Assessment
  - Peer Assessment
  - Self-Assessment

Assessment and Evaluation

ACTIVITY 6.1 EXAMPLES OF ASSESSMENT

List different types of assessment that you can think of. Classify them and make the criteria of classification explicit. You can classify in multiple ways using different criteria (e.g., level at which it is conducted, subject or domain, type of questions and purpose of assessment).

We often think of examinations or tests when we think about assessment and evaluation. However, assessment and evaluation are not limited to testing. Consider, for example, *Arangetram* at the end of learning Bharatanatyam dance or the National Achievement Survey (NAS) conducted by NCERT every three years or product evaluation carried out for a smartphone. Assessment and evaluation are used in varied fields. We often use the two terms, 'assessment' and 'evaluation' interchangeably in our daily interactions. However, there is a difference between them.

The word 'evaluation' is derived from the French *évaluer* which means 'to find the value of'. It is a systematic determination of merit, worth and significance of a product or a programme using a set of standards as criteria. Evaluation is product-oriented and judgemental. It can be carried out on a programme or a product to determine its effectiveness or usefulness. An evaluation of a programme is often done against the aims it has set for itself, though the aims themselves can be evaluated in the larger context to begin with. Such evaluation can assist organisations or companies or governments to determine whether to continue a certain programme or production and what modifications it may need. The primary purpose of evaluation is to enable reflection and assist in the identification of future change.

ACTIVITY 6.2

Evaluation of the healthcare system of a nation is an example of evaluation outside education. Think of more such examples.

In an educational context, evaluation is the final review to gauge the quality of educational programmes or institutions. It provides an opportunity to reflect on the process and identify possible changes and it is often used to demonstrate the effectiveness of the programme or institution to funders or stakeholders. Evaluation often includes a quantitative representation of students' performance in terms of gain in grades or marks. It can also include other factors such as students' engagement, parents' comfort levels with the programme, infrastructure and facilities, ability to be self-sustained or be blended in the local ecosystem, etc.

The word *assessment* is derived from the Latin word *assidere*, meaning 'to sit beside or with'. According to the original meaning of the word, the teacher is expected to sit beside the student to understand how much the student has misunderstood and what difficulties she is facing. Thus, even if assessment too can be carried out in varied contexts such as health assessment, tax assessment or environmental impact assessment, it originated in the educational context. Educational assessment is the systematic process of documenting and using empirical data on the knowledge, skills, attitudes and beliefs to refine programmes and improve student learning.

It can be carried out to find out what students already know, how much they have learned and how effective the teaching or an educational programme has been. Therefore, assessment is useful for students, parents, teachers and administrators to ensure progress.

Purpose of Assessment

In practice, the most common reasons for assessing students are screening or selection and assessment of their learning. However, lately, researchers and policymakers are advocating for 'assessment for learning' and 'assessment as learning', along with 'assessment of learning'. We will explore each of these briefly.

Screening or Selection

The assessment we know is most often conducted with this purpose in mind. The screening process is like passing students through a sieve: Those who have learned the intended content will pass to the next grade; those who have not will remain in the same grade. However, if a student has been unable to learn content with the teaching methods followed by the teacher, there is a little chance that the student will learn that content when the same teaching methods are used again. Probably, the student will only get bored while listening to everything s/he has already heard. Naturally, students who fail once, keep failing again! Moreover, they have to face the stigma associated with failure and often start believing that they are not good enough to study. There are other consequences such as losing a year and friends (who have moved to the next grade). These dire consequences make students fearful of examinations. Thus, for those who cannot perform well in examinations for various reasons, examination is more of a punishment rather than an opportunity!

Another similar reason for assessment is selecting students for a particular course (referred to as an 'entrance test') or a job (referred to as a 'competitive exam'). Here again, in countries like India, often a large number of qualified people apply for a few seats or positions. Many students study very hard for these exams because getting into these courses or jobs ensures economic stability and provides certain social status. Thus the stakes are extremely high which can create stress among the students. People often underperform when they are stressed or afraid, which results in even lower achievement in exams and the vicious circle continues. The solutions to these problems are more systemic than those which teachers can address at their level. However, it is important that they are sensitive to these problems and put pressure on the system to change these situations. After all, we all have faced this problem and we don't want our children to continue to face it!

Assessment of Learning

This is another common reason to carry out assessment. Teachers want to understand how much each student has learned. For example, when the results of mid-term exams come out, teachers know which students have mastered the content and which students lag behind. Sometimes this leads to assigning roles for students which may generate a sort of caste system within a school. For example, those who have scored well become class monitors or are asked to prepare science projects for local exhibitions, etc., and those who do not do well academically are asked to participate in 'extracurricular' activities such as drawing or sports if they show some promise in these areas or are simply asked to do odd jobs such as cleaning the board or carrying objects from one place to another!

In the best scenario, students understand how much they have learned and may decide to put in more effort so that they can score higher in the final exam. But if teachers realise that a large part of the class has not understood certain crucial concepts, do they change their strategy and try to teach it again? If this happens, it will be called 'assessment for learning' which is our next point.

Assessment for Learning

Lately it is being emphasised that assessment should be carried out to check whether intended learning is taking place. The outcome of such assessment may change the course of teaching to a small or large extent. If a teacher realises that the majority of the students have not learned the overall idea, then the teacher has to change the teaching strategy and teach the content again. If students have misunderstood a specific part then the teacher can target just that part. If a few students seem to have missed a few points, the teacher may choose to give specific feedback to them or can create learning opportunities for them separately (e.g., asking them to do certain activities at home and discussing them with a small group of students, creating a collaborative tasks in which students can learn from each other or simply giving them some extra material to read). Sometimes a teacher may realise that her students have understood the content and she may choose to go faster.

Importantly, students should be able to use the assessment to assess their own understanding. For this to happen, the outcome of the assessment for learning should not be grades or marks, it should be completely free from any kind of competition and reward or punishment and students should get immediate qualitative feedback in terms of the gaps in their understanding, or about the strategies they used for solving problems given to them. Continuous comprehensive assessment was one attempt of bringing assessment for learning in the Indian education system. We will see how assessment for learning can be enabled in the subsections on diagnostic assessment and formative assessment.

Assessment as Learning

Assessment not only provides feedback to students and teachers, but it can also create opportunities for learning. Here learning and assessment is inseparable. For example, when students are asked to do a project (design and plant a kitchen garden so that every day one vegetable is available) or solve a problem (how much wire will be required to put a compound around a circular garden of a certain area) or to do an activity and keep notes on certain observations (plant some green grams [moongs] and measure the height of a plant every day), the students will learn certain concepts as well ask skills through them. At the same time, the teacher has to continuously monitor the process, ensure that the students are able to articulate their learning and give feedback. Activity 6.1 is also an example of assessment as learning. Moreover, when students engage in peer assessment (discussed in detail later in this chapter) they learn from each other's assignments. Thus, if an assessment is designed thoughtfully, it can help students to think and lead to learning. For detailed discussion on assessment, see NCERT (2006) and Kunyakari (in press).

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Assessment in Science Education

In his review, Pellegrino (2013) asserts, 'It is well established that what we choose to assess will end up being the focus of instruction' (320). This means the kind of assessment to be done should depend upon what students are expected to learn. Recall the aims of science education discussed in the first chapter; to learn facts and principles of science, to learn skills and methods of science, to understand science as a social enterprise (nature of science), to understand issues on the interface of science, technology and society (STS issues), to prepare students for work (in STEM-related fields in particular), to nurture curiosity and creativity, to help students imbibe values such as honesty, cooperation and concern for life and to cultivate scientific temper (NCERT, 2005).

You might notice that many of the question papers only assess whether the first aim, namely to learn facts and principles of science, is met. The second aim, namely to learn skills and methods of science, is assessed to some extent in high school through practical examinations and student journals. Typical assessments rarely test students' understanding of the nature of science, their scientific knowledge in the context of their day-to-day experiences (both in the natural and social world) or their curiosity (ability to ask meaningful questions) and creativity (ability to propose novel ways to pursue those questions). One of the common aims of science education is to prepare students for work in STEM fields as discussed in Chapter 1. It follows that the objective of assessment seems to select students for these jobs. This is why a large majority of students find science irrelevant and learn it by rote, without ever questioning its content, without connecting it to their experiences and problems in daily lives and without learning any of the values in science which are of great importance in our lives in general. This has implications for inclusion, as we shall see in the next chapter.

BOX 6.1 ANAND NIKETAN PHILOSOPHY

Here is an example of how the philosophy of a school shapes its assessment practice.

Anand Niketan is a Nai Talim School[1] in Wardha. In accordance with its emphasis on daily work-related experiences, the instruction and assessment in science, among other subjects, is always in the context of some work which high school students are typically engaged in or in areas in which they help their parents such as cooking, agriculture and animal husbandry. For example, here is a question posed to grade eight students by their science teacher after teaching types of roots: Uproot at least ten different weeds in your area. Classify them as either fibrous roots or taproots.

After this activity, the students realise that if the plant has a fibrous root then it is monocotyledonous and if a plant has a taproot then it is dicotyledonous. Thus this kind of activity not only assesses cognitive skills important for science such as classification and generalisation, but it also encourages students to look at their daily experiences in a scientific way.

Even if the question in Box 6.1 assesses students' understanding of roots and sees their ability to classify and generalise, it cannot be part of the end-term question paper. Well, assessment need not always be a question paper. There are different types of assessments. Four of them, namely diagnostic assessment, formative assessment, summative assessment and large-scale learning assessment, are of particular importance in science education. These are described in the following sections along with examples.

Diagnostic Assessment

Diagnostic assessments are short assessments that focus on key knowledge and concepts. They are often carried out before starting instruction in a particular topic to understand students' prior knowledge about that topic. They also provide a baseline for understanding how much learning has taken place after the instruction is completed.

Diagnostic tests are of particular importance in science because it is well known that students often form alternative conceptions from their experience which interfere with learning science. Sometimes students form synthetic models which are a combination of students' prior conceptions and information received during instruction. Diagnostic tests can be helpful in identifying the alternative conceptions or synthetic models which in turn can dictate the course of instruction. The Force Concept Inventory (FCI) or Astronomy Diagnostic Test (ADT) are two well-known examples of diagnostic tests. Treagust (2006) provides a list of diagnostic instruments developed since 1980 which include topics such as photosynthesis, chemical bonding, light and its properties, etc. Many such tests are available online which teachers can adapt for their purpose and context.

Note that diagnostic assessments need not be in the form of tests. They can be in the form of activities or tasks too. For example, a number of interesting diagnostic tasks, including drawing pictures, were developed to understand students' ideas related to living and non-living by Chunawala, Apte, Natarajan and Ramadas (1984) and students' ideas about plants by Natarajan, Chunawala, Apte and Ramadas (1984) for the Diagnostic Learning in Primary Science (DLIPS), a project undertaken by the Homi Bhabha Centre for Science Education.

ACTIVITY 6.3 SEARCH DIAGNOSTIC TESTS

Search diagnostic tests for two topics of your interest. See which of the questions are relevant to the syllabus covered at your place. Are there certain concepts not covered in those diagnostic tests?

Formative Assessment

Teachers often ask questions while teaching; they sometimes ask students to do activities or exercises such as listing examples of certain categories or solving problems. These activities not only make the teaching interactive and constructive, but they also help teachers to assess students' learning on a continual basis. This type of assessment is called 'formative assessment'. As explained in the 'Assessment for Learning' section, teachers often change the course of their teaching in response to students' performance in the formative assessment. This type of assessment is not meant for ranking and selecting students for further levels, so the feedback is often qualitative. It is not advisable to make formative assessments formal or attach a score to them. In that case, only students' performance is assessed and their difficulties will not be revealed, which is the purpose of formative assessments.

Please note that making them informal does not mean they should not be well designed. In fact, a well-designed activity which encourages students to apply their knowledge in a specific context can be an effective tool for formative assessment. For example, a teacher can ask students to draw a concept map around certain concepts (such as 'energy'). This activity can be done individually, in pairs or small groups. For assessment, the teacher can consider the number of concepts covered and the number of correct connections. If certain concepts are multiply connected, that shows a richer understanding.

Experiments and applications of scientific knowledge are important aspects of learning science. Hence the journals which students maintain to record their observations and analyse the data or portfolio of a project can also be used for formative assessment, provided students maintain honesty. Students' skills, problem-solving ability and creativity can also be assessed along with their grip on content knowledge through such assessment methods.

There is evidence that formative assessment is effective in improving learning at all levels of education and in different cultural contexts and that it produces significant and often substantive learning gains. Moreover, frequent formative assessment and feedback are particularly helpful for low-achieving students and students with learning disabilities. This can help in preventing disruptive behaviour of students in school, drop-outs and further social problems. However, it is important to remember that assessment should be appropriate, students should be provided appropriate feedback immediately (in particular, students' motivation and self-esteem should be carefully thought about) and teachers should take feedback from it and modify the teaching plan accordingly. Some examples of formative assessment are provided in Box 6.2.

BOX 6.2 EXAMPLES OF FORMATIVE ASSESSMENT

Following are some examples used by an experienced teacher in Anand Niketan School in Nashik:[2]

1. The science teacher divided students into small groups (of five to six students) and asked them to put on a play for the eradication of

superstitions. Each group worked on it for several days and performed it in front of the rest of the class on a designated day. It was evaluated for ten marks out of which five marks were reserved for explanations of some of the gimmicks or superstitions based on the scientific principles, whereas five marks were reserved for performance (story, acting, production, etc.). All students in the group received the same marks. Such group assignments encourage collaboration among students. Here, the teacher had to be thoughtful in making groups of mixed-ability students.

2. After teaching cell structure, students were asked to express their understanding using different art forms such as making concrete models using clay or animation films through pictures. Here again, students were given a few days to complete the task. Feedback was provided on both accuracy of scientific content and aesthetics and artistry. The exhibition of all the products was put up for all the students to see and appreciate. Thus, art or other subjects can be integrated with science. This makes science more interesting and innovation and creativity get integrated with learning.
3. In another long interval assignment, after teaching the chapter on 'motion' students were asked to calculate the velocity and speed of an ant. Ants do not walk in a straight line, hence asking students to calculate their speed and velocity will make it easy for them to remember the difference. Moreover, they needed to invent various ways to calculate the distance crossed by the ant on its curved, zig-zag path. They had to try multiple ways. The teacher not only evaluated the activity on accuracy and innovation used to do this activity but also shared each other's findings and used this opportunity to talk about errors, sources of errors and the notion of average speed.

Question: Think about how you can trace the path taken by the ant and find the distance covered by it.

Source: Author.

Note that different topics may need different types of activity for formative assessment. Also, the type of activity should vary depending upon the abilities and exposure of students (standard, socio-economic status, geographical area, etc.).

ACTIVITY 6.4

Take any topic in high school science and prepare a formative assessment.

Summative Assessment

Summative assessment, as the term indicates, summarises the learning of the learner throughout the instruction. It is often used to select or screen students who would go to further levels but it can also be used to evaluate outcomes of a programme. As opposed to formative assessment, this kind of assessment often involves a score. However, similar to formative assessment, if feedback is provided after the summative assessment, learners benefit from it to a large extent. Term-end examination is the most common example of summative assessment. However, summative assessment can also be conducted after every unit or after a certain number of units are taught. In fact, it is a good idea to break the summative assessment into multiple smaller tests so that students who might be unwell or unprepared for one test get a chance to score well in another test.

It is important to design a tool for summative assessment, most commonly a question paper, which can assess all aspects of knowledge. Here is a brief discussion on preparing a question paper. It is a good practice to start with a blueprint of a question paper to ensure that all learning objectives are evaluated with respect to different types of cognitive processes and that different types of questions are included. Typically, in a blueprint learning outcomes are listed in rows and levels of student understanding are listed in columns. At the level of knowledge, revised Bloom's taxonomy is often used (Box 6.3). Please note that Bloom's taxonomy is not specific to summative assessment, it can be used to design any kind of assessment. It does play an important role in designing large-scale learning assessments as discussed in the next section. However, it may or may not be relevant in the case of diagnostic or formative assessment since the focus of these assessments can be very narrow.

BOX 6.3 REVISED BLOOM'S TAXONOMY OF COGNITIVE DOMAIN

Benjamin Bloom proposed six levels of understanding in the cognitive domain in 1956. They progress from simple to complex. This taxonomy was later revised by two of his team members, Anderson and Krathwohl, in 2001. The revised taxonomy includes cognitive processes in increasing order of complexity.

1. Remember: Facts, terms, concepts, laws, principles, theories, etc.
   Example of assessing: State Newton's law of universal gravitation.
2. Understand: Demonstrating an understanding by organising, summarising, translating, generalising, giving descriptions, etc.
   Example of assessing: Read the process of digestion among human beings and draw a flow chart of this process.

3. Apply: Problem solving, providing explanations using the laws of nature, prediction, etc.
   Example: Explain the occurrence of tides.
4. Analyse: Comparison, drawing inference, understanding the overall organisational structure, etc.
   Example: See the table of the length of the pendulum and corresponding time period and propose a relationship between these two quantities.
5. Evaluate:[3] Forming and justifying judgements about information or ideas.
   Example: Your friend believes that colonising Mars is the only way for the human race to survive in future and hence India should actively participate in the space race. Do you agree with this view? Justify your agreement or disagreement.
6. Create: Knowledge organisation, combining two seemingly different fields, producing a plan or a set of abstract relations.
   Example: What are the formulae of energy in its different forms (e.g., electric, heat, mechanical, etc.)? How are they related to each other?

Source: Anderson and Krathwohl (2001).

Traditionally a blueprint is prepared using revised Bloom's taxonomy; however, one can change the rows and columns according to your needs. For example, instead of learning outcomes, you can put topics or chapter names in rows and types of questions based on different types of cognitive processes in columns and shown in the example (Table 6.1). This is an example of a three-dimensional blueprint since each cell indicates the number of questions (and marks assigned to them) on three parameters: Cognitive process involved in responding to the question (column), type of question (sub-column) and chapter or topic (rows). Two-dimensional blueprints can also be used if further bifurcation of columns in terms of the type of question is not necessary.

In the blueprint, weightage for type of knowledge in each topic is assigned in the corresponding cell. You might have noticed that the total number of entries in columns (30) is different from the total number of entries in rows (55). This is because the total at the end of each column includes the scores for compulsory questions only. On the other hand, the total at the end of each row includes the marks assigned to a particular topic (including optional questions). Thus even if the total question paper includes questions for 55 marks in all, students are required to answer questions only for 30 marks. It is a good practice to include optional questions so that students have a choice to answer the questions they are comfortable with. Summative assessment should indicate how much students have learned as opposed to how much students have not learned. Optional questions also encourage students to use their metacognitive abilities since students

TABLE 6.1 Example of a Blueprint for a Unit Test for Grade 9 Based on the Maharashtra State Board Curriculum

Question type / *Chapter*	*Fact-based (1 mark each)*		*Reasoning-based (2 marks each)*		*Problems (3 marks each) (any 5)*	*Applications (5 marks each) (any 1)*	*Total*
	MCQ	*Other objective*⋆	*Scientific reasons (any 2)*	*Short answer (any 3)*			
Laws of Motion	1 + 1	1	2	2	3 + 3	5	18
Work and Energy	1 + 1	1 + 1	2	2	3 + 3	5	19
Measurement of Matter	1	1 + 1	2	2 + 2	3 + 3 + 3	0	18
Total	5	5	4	6	15	5	30 | 55

Source: Aksharnandan School.

Note: English translation of an original blueprint provided by an experienced teacher at Aksharnandan School, Pune.

⋆ Other objective questions include matching the pairs, true or false, odd one out, etc.

reflect on their own knowledge while deciding which questions they want to attempt and which questions they want to leave.

Teachers may choose to use different taxonomies to evaluate students' knowledge in specific subjects. An example is given in Appendix A.

Question papers typically evaluate students' declarative knowledge. Please note that summative assessment need not be a question paper. You, of course, are familiar with journals in which students write their laboratory experiments throughout the year and the journals are evaluated at the end of the year. Certain weightage is kept for the journal and the practicum component in the final score. However, we must identify appropriate criteria to evaluate them. For example, one may choose to evaluate practicum component on the following criteria:

a. Ensuring safety.
b. Motor skills (in connecting wires, measuring chemicals, handling fire, acids, etc.).
c. Knowledge about measurement procedures for physical quantities relevant to the experiment (the instrument used for measurement, its unit and least count, possible errors, etc.).
d. Ability to identify the dependent, independent and intervening variables and ensure that only one dependent variable is changed at a time and intervening variables are kept constant.
e. Data analysis (calculations, appropriate use of representation such as type of graphs or diagrams).
f. Ability to modify the experiment (because of unavailability of certain material or a slight change in aim of the experiment) or to design a new experiment (to verify results through another method).

If we encourage students to keep notes in a journal, they will hardly be neat and clean. You may encourage them to write a summary after each experiment which can be expected to be cleaner and more organised but evaluating a journal based on neatness would kill the purpose of evaluating experimental skills.

Here is another example of summative assessment used by the teacher in the Anand Niketan School, Nashik. Students were asked to do a project. Mentors were allotted and they guided the students individually. Students maintained a portfolio[4] of the project and submitted it at the end of the term. Students were evaluated against their portfolios and an oral examination.

Large-Scale Learning Assessment (LSLA)

Large-scale learning assessment (LSLA) is defined as a form of national or cross-national standardised testing that provides a snapshot of learning achievement for a group of learners in a given year and in a limited number of learning domains.

The use of these assessments has been increasing around the globe and they have also broadened in their scope. LSLAs go beyond measuring reading and mathematics and target a greater number of domains, including digital skills, computer and information literacy, socio-emotional skills, or the understanding of concepts and issues related to civics and citizenship. The two major international LSLAs in which science was included are the Programme for International Student Assessment (PISA) and Trends in International Mathematics and Science Study (TIMSS). India participated in PISA in 2009. Another important LSLA in the context of India is the National Achievement Survey undertaken by NCERT. International Olympiad exams are another example of LSLA in the area of science. In India, the Homi Bhabha Centre for Science Education conducts national-level Olympiad exams and sends selected students for the International Olympiad. The aim of Olympiads and National Talent Search (NTS) is to identify talented students in science and encourage them to pursue higher education in science, as opposed to evaluating the general status of the education system in a particular country or a state.

Some researchers argue that large-scale assessment, frequent inspections, etc. can play only a limited role in raising standards of learning. Standards can be raised only if teachers can handle their tasks more effectively (Black & Wiliam, 1998).

ACTIVITY 6.5 PISA IN INDIA

Find out more about PISA. How often is it conducted? At what level is it conducted? Go through some science questions and see whether you find them appropriate. Which nations scored high? Which nations scored low?

Where did India stand in maths and science? What did you feel about India's results? How can we explain this result? Do you think India should participate again? What can be done to improve India's scores? Write three concrete actions which you will do to improve Indian students' level of understanding in science.

Further Readings

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In this section, you came across examples of different types of assessment in some schools. Read more about these innovative schools.

Ensuring Quality of Assessment

Here are some additional tips to ensure that your assessment is well designed:

1. The question paper should have a good balance of easy and difficult questions. There should be a few easy questions, a few difficult questions and about 50% questions of average difficulty level so that the test is easy to pass but difficult to score high. Once you score the assessment, you can prepare a frequency plot. Suppose the maximum possible score is 100 (even if not, it is a good practice to convert it into a percentage). Find out the number of students in intervals of ten (say 1 to 10, 11 to 20 … 91 to 100) and prepare a bar graph for it. If the shape of the plot is like a bell (i.e., roughly follows a normal curve), it means that very few students have got very low or very high marks and most students lie in the mid-range. This indicates the difficulty level was appropriate.
2. If you plot the graph after the test and find that the test was too difficult or too easy, it will not be fair to use the test results to evaluate students and your efforts may go to waste. So it is a good practice to do pilot testing on a few students. If the number of students is not enough to plot the frequencies, you can ask students about the difficulty level. Pilot testing has other advantages as well. For example, you get a better estimate of the time required to complete the test. Moreover, you can get feedback from students and find out if some of the questions or options provided in multiple-choice questions are confusing or not clear enough. Large-scale learning assessments are always piloted and their validity and reliability are tested in various ways.
3. The questions should be phrased in different modalities so that different skills are tapped and students who have different learning styles or learning disabilities also get a chance to express their understanding. For example, a test in science should include questions which require students to respond in text, diagrams, equations, etc. Apart from text, the assessment should include oral discussion, practical work or conducting an experiment, journal of project work, etc.
4. Arranging questions from easy to difficult will help students to gain confidence and attempt the maximum possible questions. We must remember that students are under stress when they are taking exams and we must make the experience as smooth as possible.
5. Rubric: Prepare a rubric[5] for assessing students' responses before you start grading. This may include deciding how much weightage is assigned to each component of the response. For example, if the assessment includes a problem for five marks, one mark can be kept for comprehension of the problem, one mark for using correct formulae, two marks for carrying out correct calculations and one mark for using correct units in the answer. Similarly, if the assessment includes designing an experiment to test a certain hypothesis (e.g., temperature is inversely proportional to the rainfall in the day), three marks can be kept for identifying dependent, independent and intervening

variables, five marks each for inventing ways to measure dependent and independent variables while keeping the other variables constant as much as possible, five marks for analysing the data (plotting graph) and two marks for drawing correct conclusion. Naturally, the total problem will be worth 15 marks. You can convert the scores into a ten-point scale or percentage or whatever weightage this particular question has. Note that, while preparing a rubric, it is important to know which factors are difficult and may require more weightage than others.

6. Students should be aware of the portion of the syllabus which will be assessed, kind of assessment (types of question, duration,) and rubric well in advance, especially if it is a summative assessment which has consequences in terms of screening.
7. Feedback: Feedback helps students to understand their mistakes and improve, hence immediate feedback is essential after both formative and summative assessments. Feedback can be defined as 'information provided by an agent (e.g., teacher, peer, book, parent, self, experience) regarding aspects of one's performance or understanding' (Hattie & Timperley, 2007: 81). Feedback can be categorised as
   a. Feedback about a task or product (FT): Stating whether the work is correct or incorrect.
   b. Feedback about the processing of the task (FP): Providing processing information or alternative strategies.
   c. Feedback about self-regulation (FR): Providing information about self-regulatory proficiencies and self-beliefs.
   d. Feedback about the self as a person (FS): This is unrelated to performance on a task. For example, 'You can do better' or 'You are so smart!'

The first three kinds of feedback have been found to be effective in prior research, whereas the fourth is most common but least effective (Hattie & Timperley, 2007). In particular, feedback about the processing of the task and self-regulation (FP and FR) is very effective since after receiving negative feedback about a task and product (FT), school students may not be able to understand why their response was wrong.

So far we have seen examples of teachers (or evaluators in the case of LSLA) assessing students' understanding. However, that need not always be the case. We always assess our own learning and each other's knowledge. In the following section, we will discuss peer assessment and self-assessment.

Further Readings

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Peer Assessment and Self-Assessment

Peer Assessment

Formative assessment can greatly benefit from peer assessment because peers can provide quick feedback which is in the zone of proximal development for students. In many of the examples provided in Box 6.2 in the section on formative assessment, the teacher from Anand Niketan (Nashik) used peer assessment. For instance, in the first example, when one group performed their play on the eradication of superstitions, it was assessed by the rest of the class. Peers were encouraged to give qualitative feedback in terms of what the things they liked were, what could be improved and whether there were any mistakes in the explanations and justify their marks. The final marks were assigned based on the average of all groups. Note that peer assessment can be used in combination with teacher's assessment with a certain weightage reserved for each.

ACTIVITY 6.6 ENGAGE IN PEER ASSESSMENT

You have prepared a tool for formative assessment in Activity 6.4. Use this tool for peer assessment in the following way. Before you start, the class has to come up with criteria of assessment together. For example, you can decide that the maximum possible score will be ten, out of which three marks are for properly written information about the tool (topic, grade level, aims, etc.), three marks are for accuracy and clarity of questions and four marks are for innovativeness. Once you finalise the rubric, each tool has to be assessed by two of your peers and each person should assess two tools. You can do this by drawing chits so that your tool gets assigned to any two random peers. Now give marks with feedback. Did you benefit from your peers' comments? Did you learn something while assessing two of your peers' tools?

Self-Assessment

Another interesting possibility is to create opportunities for self-assessment. Self-assessment is beneficial because it is the least threatening for students. Moreover, it inculcates metacognition among students. One of the easy ways to do this is to give a question paper or task to students and ask them to attempt it. Once they complete the task, provide the answer key and let the students check their responses. Then ask them to write down their mistakes or the topics which are still unclear. Finally, ask them to rewrite the questions they missed. Strictly avoid the temptation of asking for their marks! This method is often used in textbooks of higher standards, but unless students attempt the questions they missed, they will not benefit from this kind of self-assessment. Also, note that this method works when questions or problems have definite answers. They may not be very effective for more open-ended questions.

Another way to encourage self-assessment is to break down the entire chapter after teaching is complete and ask students to reflect on their understanding. You can ask them to tick mark the topic they have understood and encourage them to read the topics again or ask questions on the parts they have not understood well. However, this method works well when students have good metacognitive abilities.

One of the interesting ways in which the science teacher from Anand Niketan School (Nashik) used self-assessment was that she asked the students to prepare a question paper on certain topics. While preparing the questions, students were forced to reflect on their own understanding and they read the chapter again to refine their questions (and answers). The teacher too got the sense of the depth of her students' understanding since students who understood the topics and the connections between different topics well could come up with more insightful and innovative questions. The teacher used some of the questions in the final question paper with slight modification, which was in a way a reward to the students who used the opportunity of self-assessment well!

ACTIVITY 6.7 ENGAGE IN SELF-ASSESSMENT

Now that you have read the entire chapter carefully, keep it aside. Write a summary of this chapter without referring to the chapter. Now browse through the chapter again and identify the important points you may have missed or the information which you could not remember properly. Include it in your summary.

Further Readings

Corrigan, D., Gunstone, R., & Jones, A. (Eds.). (2013). *Valuing assessment in science education: Pedagogy, curriculum, policy*. Springer.

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SUMMARY

In this chapter, we learnt:

- Meanings of the words 'assessment' and 'evaluation' and the difference between the two.
- The purpose of assessment should not be limited to screening and selection. Assessment of learning, assessment for learning and assessment as learning can make assessment less threatening and more useful for learning.

- Assessment in science should be prepared in accordance with the aims of science education.
- Assessment need not always be a question paper. We should think of ways of assessing in which students can engage in a variety of tasks and can express themselves in different ways.
- Diagnostic assessments are useful in understanding students' prior knowledge, which includes their alternative conceptions. They also provide a baseline if we are interested in measuring learning gains.
- Formative assessment plays a key role in teaching and learning. Formative assessment can often be informal and marks are not associated with it. Immediate feedback needs to be provided after formative assessment. It is particularly useful for low achievers. Peer assessment can be effectively combined with formative assessment.
- Summative assessment is most commonly in the form of a question paper, but it can be in different forms such as journals or portfolios of projects, etc. Using a blueprint can improve the quality of the question paper. Other forms of summative assessment should be accompanied by a rubric of assessment.
- Large-scale learning assessment can give an overall picture of the status of the education system in a state or a nation. We can use them to understand where we are in comparison with the rest of the world. They also indicate trends such as sex differences, differences in different populations, etc. However, they may not be very useful in improving the teaching-learning process in schools.
- Quality of assessment can be improved by pilot testing the question paper on a smaller sample, ensuring a good balance of easy and difficult questions, arranging questions from easy to difficult, providing ample optional questions and including different types of questions.
- Self-assessment is a respectful way of assessment with great potential.

Exercises and Practice Questions

1. Write down the differences and similarities between educational evaluation and educational assessment.
2. Take science question papers from any two grades. Analyse them with reference to the aims of science education for those grades. How much weightage is given to each aim? Are there any aims completely left out from the question paper? What could be the reasons? Can you think of ways to accommodate the aims of science education which might be left out from common forms of assessment?

3. Design at least two innovative summative assessments. One of them should be a question paper and the other should not be a question paper. For both assessments, write down:
   - What it aims to evaluate.
   - What its strengths and weaknesses are.

   For the question paper: Take any topic or a number of topics in high school science and think of what you would put in rows and columns to make a fair assessment. (Remember, what you put in rows and columns of a blueprint changes according to the requirements of the test.) Prepare a blueprint and the corresponding question paper.

   For the other assessment: Prepare a rubric for assessment.
4. Here are some of the questions in the question paper for Vidnyan Ranjan Spardha 2021, organised by Marathi Vidnyan Parishad Pune Vibhag. Look at the variety of questions carefully. Now analyse this question paper using Bloom's taxonomy. Have all levels of understanding been assessed? If not, what levels are left?
   1. How many leaves does a stick of curry-leaf have? (observe and answer)
   2. How much salt dissolves in 100 ml of water? (observe and answer)
   3. How many times the length of rubber is stretched? (observe and answer)
   4. I am a disease. The first experiment of vaccination was done on me. Who am I?
   5. I started the Chipko movement. I received the Gandhi Peace Prize in 2013. Who am I?
   6. I am a flower spread over 111 cm. Who am I?
   7. We kill or catch germs in the body. Who are we?
   8. What alternatives can be used for food packaging instead of plastic?
   9. Make a list of activities, processes and items that cause air pollution in the house.
   10. What advertising on television do you think makes unscientific claims?
   11. What are the cheap and easily available alternatives to Bournvita or similar food items in your home?
   12. The salinity of the beach is due to mangroves. Right or wrong? Explain in brief.
   13. If the corner of the plastic milk bag is cut and thrown away, there is no harm to the living beings. right or wrong? Explain in brief.
   14. Curly hair is a genetic trait. Right or wrong? Explain in brief.
   15. Why does milk overflow while boiling?
   16. Soap does not foam in saltwater? Give scientific reason.
   17. Cumin seeds/mustard seeds are added first in hot oil Tadka. Give the scientific reason.

18. On a cold day, fog is seen coming out of the mouth. Give the scientific reason.
19. What are the ingredients in home spices like flowers, bark, leaves, fruits and minerals?
20. What are the signs before a drought occurs?
21. Draw a water cycle. Show where and what effect man has had on the water cycle with coloured ink.
22. Graph the time of sunrise and moonrise from 1 to 10 February. What is the conclusion?
23. What is the mechanism of operating a stage curtain that opens up on both sides? Draw a picture and write the answer.
24. Try it out and answer: What should be the ratio of the height of the pot to the height of the milk in it so that the milk does not overflow?
25. Write an essay: What are the studies that need to be done before a drug/vaccine can be marketed as a specific remedy for a disease?

To access this and other older question papers, visit http://mavipapune.com/mpp/

Notes

1 Nai Talim, also known as Buniyadi Shikshan or Basic Education, is an education system proposed by Mahatma Gandhi. It aims for holistic development (body, mind and soul) and does not separate learning from working. In particular, it puts emphasis on handicraft and manual labour.

2 This is a different school from the one mentioned earlier in Wardha.

3 According to the original version, 'evaluation' (evaluate) comes after 'synthesis' (create) but the order was changed in the revision since creation is possible only after one is able to evaluate the content.

4 A portfolio means a large, thin, flat case for loose sheets of paper such as drawings or maps. In this case, where students are engaged in a project, students can keep the records of all their observations, pieces of information they gathered through various sources, discussion, ideas, etc. in a large folder. This allows flexible arrangement of different kinds of documents (such as newspaper clippings, graph papers, photographs, sketches, etc.) from more than one participant. It also allows participants to compile their documents at the time of final submission. For example, they may want to add a summary or some evidence post-facto or they may choose to leave out the documents on the ideas which they discarded in the process or which are redundant.

5 Rubric is a set of criteria to evaluate students' responses.

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Appendix A

Here is an example of a taxonomy which is different from Bloom's taxonomy to assess students' knowledge in a specific subject, namely astronomy. The following type of blueprint can be used (Table 6.2).

Examples of some of the questions in each cell:

Earth – Observational (textual): Have you heard the word 'horizon'? What does it mean? (2 marks)

Sun – Observational (textual): What is the colour of the setting sun? (1 mark)

Sun – Observational (diagrammatic): Imagine a person standing on a playground. Draw the position of the sun for that person at 7 am, noon and 5 pm. Mark the directions. (5 marks)

Moon – Observational (textual): Does the moon change its apparent position or does it remain the same throughout the night? (1 mark)

Moon – Observational (diagrammatic): Draw the following phases of the moon in one phase cycle as you remember them: Full moon, waning gibbous, waning half-moon, waning crescent, new moon, waxing crescent, waxing half-moon, waxing gibbous, full moon. (9 marks)

TABLE 6.2 Blueprint of the Questionnaire to Assess High School Students' Knowledge in the Area of Astronomy

Knowledge type	*Observational*		*Mental models*		*Explanations or predictions based on models*		*Indigenous information**
Question type	*Textual*	*Diagrammatic*	*Textual*	*Diagrammatic*	*Textual*	*Diagrammatic*	*Textual only*
Earth	1 × 2	0	1 × 5	5 × 3			
Sun	5 × 1	1 × 5	1 × 5	1 × 7 + 1 × 8			
Moon	5 × 1	1 × 9 + 1 × 1	1 × 5	10 × 2			
Planets	10 × 1	1 × 3	1 × 10	10 × 1			
Other objects in solar system**	1 × 4 + 4 × 1	4 × 3	1 × 5	3 × 2 + 4 × 1			
Total	30	30	30	60			

Source: Author.

Note: Each cell gives the number of questions multiplied by marks for each question.

* Indigenous information includes knowledge coming from indigenous sources such as local calendars, mythology, folklore, festivals, etc. (e.g., the relation between seasons and the apparent path of the sun, phase of the moon on particular festivals such as Diwali, Eid or Buddha Poornima) and beliefs (typically astrological).

** Other objects in the solar system include moons of other planets, comets, asteroids and meteors.

Planets – Observational (textual): Which planets have you seen through your naked eyes? (4 marks)
Planets – Observational (diagrammatic): If you have seen Saturn through a telescope, draw its picture. (3 marks)
:
:
Other objects in the solar system – Indigenous knowledge: What do you know about comets?

7

INCLUSIVE SCIENCE EDUCATION

जाति न पूछो साधु की, पूछ लीजिये ज्ञान।
मोल करो तलवार का, पड़ा रहन दो म्यान॥

– कबीर दास

Don't ask caste of a monk, ask for knowledge. Value the sword, set aside the sheath.

– Kabir Das

OBJECTIVES

The objectives of this chapter are to help you:

- recognise the need for inclusion in science education.
- become critically aware of the role of teachers and the larger system towards ensuring inclusive education.
- learn about several efforts towards inclusive science education in the country.
- understand the perspectives of multicultural education.
- use principles of Universal Design for Learning to design inclusive classrooms.

The chapter is divided into three sections. The first section looks at "why" inclusion is important in science education. In the second section, we will learn about curricular and pedagogical initiatives in India that have attempted to make science education equitable and inclusive. And, in the final section, we will discuss how we can create inclusive classrooms. The chapter is organised as follows:

DOI: 10.4324/9781003047506-8

- Barriers in STEM Learning
  - Why Are Diversity and Inclusion Important?
  - Barriers to Participation in STEM
  - Culture and STEM Education
- Inclusive Science Learning
  - Universal Design for Learning
  - Integrating UDL and PCK
- Examples of Inclusive Science Approaches in Practice
- Summary

Barriers in STEM Learning

We often think that the only important thing in scientific work is the quality of research done by the scientist. However, it is becoming clearer that in reality, wealth and the background of the people doing science matters when it comes to who gets to participate in science-related fields. Participation in science and taking up science careers are not equally distributed across different groups in society. The elite and the powerful groups in a society are more likely to take up science at the higher education level and eventually end up practising science. This is true across a number of countries. In India participation in science is much more in the case of male, urban, English-speaking and upper-caste groups (Padma, 2016). As Thomas (2020) writes,

> The domination of Brahmin and the upper caste scientists have given a Brahmanical identity to science in India. They have been perceived to be the natural inheritors of scientific practice, an assertion reaffirmed by scientists and researchers during my fieldwork in Bangalore, India. Furthermore, merit and passion for doing science was reinscribed and calibrated to denote the alleged castelessness and objectivity of science, obfuscating the deep hierarchies of caste in the practice of science in India.
>
> *(1)*

Elite domination of science is a cause for concern both from the point of view of scientific development and also from the point of view of equity and justice. It is now widely accepted that scientific work benefits from diversity. The next section discusses this.

Why Are Diversity and Inclusion Important?

Diversity has many aspects, such as family background, age, gender, sexual orientation, caste, ethnicity, culture, religion, geography, disability, socio-economic status, area of expertise, level of experience, thinking style and skill set. Diverse groups are typically smarter and stronger than homogeneous groups when innovation is a critical goal (Page, 2007). There is considerable evidence that shows that teams having greater diversity among members do better than homogeneous groups on complex tasks, problem solving, innovation and making more accurate predictions (Page et al., 2017; Freeman & Huang, 2014; AlShebli et al., 2018). Diverse and inclusive scientific teams can generate new research questions that have yet to be asked in a given field, develop methodical and analytical approaches to better understand study populations and offer approaches to problem solving from multiple and different perspectives. In science, diverse groups published higher numbers of articles, and these receive more citations per article (Adams, 2013).

When it comes to science, technology, engineering and math (STEM) education, initiatives that promote diversity positively affect both minority and majority students in terms of student attitudes towards ethnicity, institutional satisfaction and academic growth (Smith, 1997). According to Anderson (2008), diversity promotes learning goals such as tolerance of ambiguity and paradox, critical thinking and creativity. The work of Gurin and colleagues (2002) indicates that students who experienced the most diversity in classroom settings and in informal peer interactions showed the most engagement in active thinking processes, growth motivation and growth in intellectual and academic skills. They also found that students who experience diversity in classroom settings and in informal interactions show the most engagement in various forms of citizenship and the most engagement with people from different backgrounds and cultures.

We can conclude, therefore, that the practice of science as well as science education needs to actively encourage participation from as wide a cross-section of society as possible. By making science education more inclusive we can ensure that more students from disadvantaged groups will develop an interest in science and take up careers in science. However, there are many barriers that prevent students from weaker sections of society from pursuing science.

ACTIVITY 7.1

Read biographies of a few scientists and reflect on how these aspects influenced their life – upbringing, culture, nationality, socio-economic background, talents, abilities and interests. Some of the scientists that you read about may have/had disabilities.

A few of the very famous ones include Isaac Newton (who stuttered heavily), Thomas Alva Edison (who was hearing impaired and had a learning disability), Albert Einstein (who had Asperger's syndrome, a type of autism) and Stephen Hawking (who suffered from motor neuron disease; doctors had told Hawking that he would live for a year when he was 21 – he passed away in 2018 at the age of 76).

Think that if they had been excluded from science, they would not have been able to make their immense contributions that have impacted our lives so deeply.

Barriers to Participation in STEM

Students who are female, from lower castes, from rural or tribal backgrounds, have poor knowledge of English or have any form of disability are all less likely to go for STEM-related courses. According to Indian chemist and educationist, Professor Gautam Desiraju from the Indian Institute of Science, Bengaluru, the chances of rural students in STEM are hampered by the lack of good science teachers and lab facilities in their schools. The problem is compounded by the fact that these children are often unaware of various opportunities to enter mainstream science. Rural girls face still more hurdles and are often discouraged from pursuing higher studies or jobs. Girls from poor urban families face pressure to enter the labour force at a young age in order to support their families and save money for their own marriage and dowry (Padma, 2016). Even when girls from urban middle and upper classes get into science, that decision is made keeping in mind the family status, the future marriage prospects for the girl and accepted norms for women in their communities and classes (Gupta, 2020).

Gender

Though India has made good progress since independence in women's education, there is still a long way to go for the gender gap in STEM fields to close. According to the latest data from the All India Survey on Higher Education 2019–2020, the percentage of women earning PhDs in the traditional sciences such as biology, chemistry and physics is almost similar to that of men (Ministry of Education, 2020). However, the Indian science gender gap is most dramatic in engineering and technology fields. The gender gap seems most persistent and significant at the most prestigious engineering and science institutions, such as the Indian Institutes of Technology (Mukhopadhyay, 2018). Far more males than females are currently enrolled in 'diploma' programmes, which may cover subjects like computers and electronics taught at polytechnic institutes and management taught at the elite Indian Institutes of Management (IIMs) (Government of India, 2016; Mukhopadhyay, 2018). Therefore, we can see that while statistics for women's presence in higher education in science have improved overall, their participation in the elite Institutes of National Importance is much worse compared to men's.

Gender disparity with regards to STEM can be traced to two broad causes in India: a) historical disparities in the education of boys and girls and b) the role of the family in educational decision-making (Mukhopadhyay & Seymour, 1994.) Historically, disparities in girls' and boys' education have been observed at every level of schooling, but they were especially noticeable at the secondary and higher secondary stages of schooling. By the time of college education, where students can take up science and engineering degrees, the ratio of girls had been significantly lower than that of boys. This factor predominantly explains why we see so few women at STEM-related workplaces and even fewer of them in powerful, decision-making positions in scientific institutions. When it comes to the family's role in educational decisions, Mukhopadhyay (2018) suggests that 'Indian educational decisions are family decisions, which had broader family, social, economic, and status impacts and involved substantial investment of resources' (62). Since educational decisions are made by the family, and not by the individual student, they are guided by collective family concerns and goals. Different obligations to family for boys and girls lead to different educational expectations and goals for sons and daughters. This situation leads to family educational investments that favour boys over girls. Since families are also concerned about girls' 'character' and marriageability, the education of daughters can potentially become socially problematic.

Language

In India, language too can act as a barrier to participation in science. Not knowing English sufficiently well works to the disadvantage of rural students, since many elite colleges and universities teach science in English. Selection into universities and prestigious research institutions often involves a written exam followed by an interview, and teachers in interview selection committees often are biased against students who cannot respond in proper English (Padma, 2016). Even if students who learn in vernacular medium schools do enter universities for higher education and training in science, lectures delivered in English often act as a hindrance. Consider this quote from a Scheduled Caste student in a large elite university in India:

> I feel nervous to approach teachers. We could not understand many of the lectures at first. They speak English very fast. Only the toppers can understand. But we will not ask any questions. 'Why are you asking such silly questions?' the teacher may ask.
>
> *(quoted in Tierney et al., 2019: 9)*

Disability

Fifteen per cent of the world's population, or approximately one billion people, experience some form of disability. Developing countries like India often have a higher prevalence of disabilities of several kinds. 'Persons with disabilities include those who have long-term physical, mental, intellectual or sensory impairments which in interaction with various barriers may hinder their full and effective participation in society on an equal basis with others' (UNCRPD, 2006: 4). And evidently, individuals with disabilities are much less likely to be found in science-related careers. In India, among visually impaired individuals, a higher percentage takes up careers in commerce or humanities disciplines than in science (Research Matters, 2017).

Science and math college students with disabilities in the US also reported facing many barriers (Seymour & Hunter, 1998). When faculty were requested to make accommodations or adaptations for students with disabilities their responses included either asking students to drop the course or giving lower grades for the accommodation of special needs. Sometimes, there were blunt refusals to accommodate, saying that they were preparing students for 'real world' competition and a number of times, students were embarrassed by teachers when the latter talked about their disability and needs for accommodation in front of their peers (Seymour & Hunter, 1998). This illustrates that often the most serious barrier faced by persons with disability is attitudinal rather than physical.

> Negative attitudes have been identified as the single greatest barrier faced by individuals with disabilities who are pursuing a career in STEM fields. Educators, fellow students, employers, and co-workers, who embrace diversity, often find themselves working with gifted people whose abilities far outweigh their disabilities.
>
> *(Research Matters, 2017)*

Further Readings

Chadha, G., & Achuthan, A. (2017). Feminist science studies. *Economic and Political Weekly*, *52*(17), 7–8.

Subramanian, A. (2015). Making merit: The Indian Institutes of Technology and the social life of caste. *Comparative Studies in Society and History*, *57*(2), 291–322.

Culture and STEM education

In this section, 'culture' of science refers to the stated and unstated customs and behaviours, norms and values that are normative within STEM education. Students' interest, self-concept and persistence in STEM disciplines are affected by the culture of science, technology, engineering and mathematics education they receive.

> College campuses and the STEM departments and programs in them represent distinct types of organizational settings, with cultures created and perpetuated by physical structures, policies, underlying values, and social norms that guide their functioning. The cultures that students experience shape their awareness and understanding of standards, expectations, and their belonging.
>
> *(Malcome & Feder, 2016: 60)*

In India, a number of Dalit and tribal students complain of systemic, frequent ways in which they feel isolated, humiliated and marginalised in Indian science establishments. They often do not receive any support from their teachers, and examiners they encounter ask them about their caste backgrounds. As mentioned earlier, lack of command over English and limited exposure to middle-class popular culture often come in their way of interacting with fellow students and professors, leading to their isolation and absence from important social networks (Biswas, 2016; Tierney et al., 2019). The tragic suicides of Dalit students like Rohith Vemula at the University of Hyderabad and Balmukund Bharti at the All India Institute of Medical Science (AIIMS, New Delhi) at elite STEM institutes have brought into focus the significance of institutional cultures in supporting the education of students from diverse groups such as women, Dalits, Adivasis and religious minorities. As noted in the introduction of this chapter, the culture of science in India is Brahminical and this can lead to students from other groups feeling excluded.

At the global level, the 'relationship between institutional or disciplinary culture and race, ethnicity, and gender is especially relevant in STEM fields, where racial and ethnic minorities and women are even more underrepresented than they are in most other fields' (Anderson et al., 2006). Similar to racial discriminations in the USA, caste-based discriminations persist widely in India across institutions and this negatively impacts students from non-dominant groups who wish to pursue studies within these institutions. Gender- and caste-based discrimination came together for Sujatha Gidla, an author, who was jailed for participating in a strike against an upper-caste professor in her engineering department, who was deliberately failing students from the lower castes. She was the only woman who had participated in the strike. The protestors were all jailed in an undisclosed location. Gidla was detained for three months, during which she was tortured and contracted tuberculosis (Gidla, 2017). Institutional cultures with hostile or unwelcoming environments have been related to social and academic withdrawal, isolation and many other negative consequences for students who experience such hostility.

Distinct from larger institutional cultures, STEM learning can be viewed as a cultural process in which the practices and assumptions of STEM education reflect the culture, cultural practices and cultural values of STEM professionals (National Research Council, 2009). Drawing from cultural anthropology, some science educators have studied how students' home backgrounds and cultures affect their success in learning science. These studies indicate that how effectively students move between the cultures they are familiar with and the 'culture' of school science depends, among other factors, on the extent of assistance students receive in making those transitions easier (Aikenhead, 1997). Students must deal with and work their way through to reconcile differences between their culturally drawn epistemological beliefs and those of mainstream science contexts (Nelson-Barber & Estrin, 1995). This barrier is particularly salient for students from indigenous communities whose ways of knowing and views of the natural world often diverge from those present in STEM classrooms (Aikenhead, 1998; Bang et al., 2007; Cobern & Aikenhead, 1998). These students may be marginalised by STEM instruction that portrays scientific ways of knowing as free from value and above the influence of context because such instruction is at odds with their cultural self-identity (Aikenhead & Ogawa, 2007). In fact, Aikenhead

(2001) argues that only a small minority of students have world views and self-identities that align with the ways of knowing frequently conveyed in STEM classrooms. He also suggests that the marginalisation of students who struggle with the 'border crossings' in the science classroom can be reduced by explicitly coaching students to cross those cultural borders (Aikenhead, 1996).

ACTIVITY 7.2

Recall from Chapter 2 that science is not a value-free endeavour. In what ways do societal biases and prejudices impact the values and ethics followed by individual scientists? Illustrate with examples.

Inclusive Science Learning

In the last section, we saw science education is not inclusive. The problem becomes more acute as we advance to higher levels of education. Far fewer children with physical and learning disabilities, lower caste, low socio-economic strata and language barriers enter and thrive in school science education and therefore we find them less represented in mainstream science careers and jobs.

While it may appear that concerns of inclusion and equity in science education are relatively recent, governments and civil society groups had grasped the problem of the exclusionary nature of science much earlier. Curricular and pedagogical initiatives to provide good science education to those who are least likely to receive it through formal mechanisms of schooling have existed at least from the 1970s in the country. In this section, we provide an overview of some notable initiatives that have strived to make science education more equitable by taking science to marginalised students.

We start with enumerating some systemic efforts taken by various agencies for science education. One of the oldest and longest-running of such efforts was the Hoshangabad Science Teaching Programme (HSTP) which ran for almost three decades in the government schools of Hoshangabad district, Madhya Pradesh. From 1972 to 2003, middle-school children were learning science by doing, by engaging in authentic scientific inquiry practices and by learning from their local environment. This innovative programme was implemented by Kishore Bharati and Friends Rural Centre in collaboration with the Government of Madhya Pradesh in a number of schools starting from the district of Hoshangabad. HSTP engaged in producing new textbooks, orienting teachers in child-centred pedagogy, working with children and providing low-cost, locally sourced science kits to its partner schools. While the programme does not run anymore, it has been a pioneer in improving science education for all children including children from tribal regions in the state and across the country (Eklavya, 2021).

ACTIVITY 7.3

Read up on the history and activities of HSTP with the resources provided here. Do you think you would have liked to be a student in an HSTP-inspired classroom? Think of reasons for your answer and reflect on what you can do to become a teacher who teaches science in a similar manner to all the students.

Some policy documents and curriculum reform efforts have acknowledged the diversity of students, their cultures, learning needs, and their local environments across the country and noted that educational experience of children should take into consideration their diverse contexts. Two of the most influential national initiatives that have shaped prevalent discourse on education are the Yashpal Committee Report titled *Learning Without Burden* (1993) and the National Curriculum Framework 2005. Both of these documents recognised the need for curriculum to be context specific, and underscored that textbook writing processes should be decentralised. The *Learning Without Burden* report, framed under the chairpersonship of Professor Yash Pal, an eminent scientist and educationist, emphasised a conceptualisation of knowledge as living and actively constructed by learners. The NCF 2005 rooted in the same view of knowledge and learning paved the way for a kind of curriculum which would be responsive to students' needs and contexts. It brought the issue of children's needs, desires, motivations and backgrounds into the centre of educational thinking and organisation.

While these initiatives are a part of the formal space of school education, several initiatives also target the non-formal spaces of science education. The presence of institutions like planetariums and science centres works to increase students' interests in science by making them engage with scientific knowledge in an interesting manner. Because they charge a minimal fee, students from non-elite schools can visit them and get fascinated by scientific artefacts and multimedia representations of scientific concepts and the natural world.

A number of more localised initiatives that take science to diverse publics have existed outside the ambit of the government plans and schemes. For instance, Arvind Gupta Toys is a repository of resources on how to make science 'toys' and other educational materials to carry out or demonstrate science experiments and concepts in low-cost fashion. The website, arvindguptatoys.com, is also an impressive collection of web resources for teaching and learning of science in English, Hindi, Marathi and other Indian languages. Generating low-cost, accessible resources from locally available materials for effective science teaching has been an area where a number of contributions have been made. The Homi Bhabha Centre for Science Education, TIFR, Mumbai has been involved in designing curricular materials, resources and at the same time conducting teacher professional workshops to make activity-based and effective science learning available to students from rural and tribal regions of the country.

Apart from resource generation and teacher professional development, a number of initiatives have existed in the field of 'science popularisation'. These initiatives have been guided by the desire to take scientific knowledge, which often stays confined in the ivory towers of research institutions, to the general public. Making scientific knowledge accessible, or science popularisation, is usually coupled with the aim of inculcating 'scientific temper' among the common people, to increase their capacity to act rationally, to engage in evidence-based logical thinking and to not believe in superstitions which have no scientific basis. Such efforts have been made in different states by voluntary organisations at their local level, and have endeavoured to reach those living in rural and tribal regions in their own language. Founded in 1962, the Kerala Sasthra Sahithya Parishad was, and continues to be, a people's science movement consisting of science teachers and writers. Its mission has been to take science and technology to people so that their benefits do not go to a small privileged group but to all the members of society. One of its initial activities was to publish science literature in Malayalam, and thus to popularise science in this way. Another such mass movement which aims for social transformation through science and technology is Bharat Gyan Vigyan Samithi. It began its effort to create a demand for education among the neglected masses and has gradually evolved into an organisation aiming to create a fully literate society, with a focus on taking scientific methods and techniques to the people and thereby inculcating scientific temper in the society. Similarly, there is the Tamil Nadu Science Forum (TNSF), Assam Science Society, All India People's Science Network and so on.

Through the ongoing discussion, we can appreciate that while there have been scattered efforts from the government and civil society to address the learning needs of students, the educational system as a whole has stayed much the same. Universalisation of education with the implementation of the Right to Education Act 2010 has been successful in increasing student enrolments in schools, but the formal practice of education still struggles to make learning meaningful for marginalised children in school. The recent National Education Policy 2020 acknowledges this:

> While the Indian education system and successive government policies have made steady progress towards bridging gender and social category gaps in all levels of school education, large disparities still remain – especially at the secondary level – particularly for socio-economically disadvantaged groups that have been historically underrepresented in education … While overall enrolments in schools decline steadily from Grade 1 to Grade 12, this decline in enrolments is significantly more pronounced for many of these SEDGs, with even greater declines for female students within each of these SEDGs and often even steeper in higher education.
>
> *(Government of India, 2020: 24)*

To enable students from disadvantaged groups to participate in science classrooms and to prevent science from reinforcing existing structures of dominance in society, science teaching should be planned keeping in mind the diverse barriers that the gender, caste, language, physical and learning disabilities, geographical context and socio-economic status of a learner can create. In the next section, we discuss some frameworks with illustrative examples to show how science teaching can be designed for meaningful inclusion of all students.

Further Reading

Kannan, K. P. (1990). Secularism and people's science movement in India. *Economic and Political Weekly*, *25*(6), 311–313.

ACTIVITY 7.4

Read the following narrative and discuss the questions that follow.

Famida teaches English and Science to grades 6 and 7. It is a multi-grade class with 46 students, who are at different reading levels. Today she has planned for a guided reading session for two periods of 80 minutes total duration. Read Famida's following account of how she organised the class.

Grouping and Resources

First, I made the students sit in six groups: five groups of eight and one group of six. I took the help of four students to organise the seating, calling out the name of each student and assigning a group to him or her. While assigning a student to each group, I was careful to ensure that students of similar reading abilities were grouped together. Students in one group can barely read and I gave this group a big book I had used at the beginning of the year, based on a grade 2 text. Students in two groups could read fairly fluently. To one of these groups, I gave storybooks on science themes I had borrowed from the school library; to the other, I gave a collection of simple stories I has been compiling from the students' section of newspapers. Students in two other groups were familiar with letters and sounds and could recognise some sight words, so I told them to use their science textbook chapter.

The six students in the last group are those that require special help: one child is blind, one is dyslexic and four were migrant students who had joined the school only ten days earlier. I gave the blind child tactile letters that I had cut out from sandpaper, as was advised in the training on inclusive education I had attended in the summer. I told her to feel these letters and guess what they were, and that I would come back to help her. To the other five, I gave a large picture book that my own son has now outgrown reading. I told this group to take turns to read the picture book and talk quietly about what they could see in the pictures, and that I would come back to help them.

Monitoring and Assessment

I planned to observe three groups of students: two that are struggling to read and one that has students who are fluent readers. Within the 80-minute double period, I also wanted to ensure that I spent time with all the groups of students.

Once the students settled in their groups, I spent about five minutes moving around from group to group ensuring that they were all reading and had understood what was expected of them. Once I was satisfied they were settled, I spent 10–15 minutes with each group, listening to each student read a portion of the story, helping them where needed, and asking them questions to gauge how much they had comprehended what they had read. As I did this, I used a checklist I had prepared beforehand against each student and made very brief notes where necessary.

Classroom Management

By the time I reached the third group, two students in another group had started quarrelling. Most students in the first group had finished reading what was assigned to them and were clamouring for my attention. For a moment, I must admit, I felt flustered. I had planned to spend more time with the third group because they have been struggling to read, despite their best efforts. I had to act quickly: I separated the two students who were quarrelling and put them into different groups, telling them to help others and that I would be watching them to see if they achieve this. I asked some of the students who had finished reading to make drawings in their notebooks, depicting the story. I asked two others to read aloud the picture book to the last group. Only then was I able to spend the next 20 minutes with the third group.

By this time, the noise level in the class had been steadily rising as students had either finished reading or become restless. I tried my counting strategy; my students know that when I start counting slowly up to five, they must settle back into their places and stop making noise. Only five minutes were left before it was the lunch break. I quickly gave them homework – an assignment of reading and copying the label of any three food products they find in their house or neighbourhood shop. I called the last group of six students aside and asked them to draw any three products and write the first letter as their home assignment. I asked the blind student to ask her mother to name three products and for her to repeat them in the next class. I plan to teach food and nutrition in the next class.

I made a note in my diary soon after the bell: To make time in the next class to work with students in the group who were given the library books, and list the names of students who I did not hear read that day.

Source: Author.

Questions for Discussion

- What strategies make this an example for an authentic and inclusive learning environment?
- What makes this learning environment authentic?
- How does the teacher assess the children?
- How will you be able to adapt these strategies in your classroom?

Universal Design for Learning

We now move on to how teachers can make science classrooms inclusive for students irrespective of the backgrounds they come from and their abilities. Teacher preparation or teacher empowerment is a primary tool to effect change for including all children in science learning.

Throughout the book, we have seen several examples of how the framework of pedagogical content knowledge can be utilised to better prepare science teachers. This framework is highly useful when it comes to equipping teachers with relevant knowledge so that they can teach science in a more effective manner. But when it comes to ensuring that *all* students in the classroom feel included or are able to participate in science lessons, the framework does not provide many practical solutions. Some versions of the concept have included in the framework teachers' knowledge of common alternative conceptions that students may have on a given topic, and the knowledge of aspects of a topic students find interesting, difficult or easy to learn (Gudmundsdottir & Shulman, 1987). But these aspects of student learning still remain limited to their cognitive processes. It is now established that there exists a deep and strong relationship between students' participation in science classrooms, consequently their learning and performance, and their social and cultural backgrounds as discussed in the previous section. The culture of school science – the ways of talking, behaving, interacting, reading and being in a science class – is often opposed to the cultures of marginalised groups of society. For such students, then, science education is much more than learning scientific content; it takes a form of initiation into a different culture, a different way of looking at and making sense of the world. This phenomenon is often referred to as 'border crossing', and the task of the teacher then is to assist students in this process (Barton & Tan, 2009).

The Universal Design for Learning (UDL) framework offers both a philosophical basis and a set of guiding principles to ensure the learning environment is enriched to meet the needs of every learner (Rose et al., 2006). The philosophy of UDL is that there are multiple means of representing knowledge, engaging students and assessing students for their understanding. The UDL framework is based on three principles, each with a set of comprehensive guidelines for using resources and tools that ensure every student can learn. Teachers can use these guidelines to make knowledge more accessible, increase student engagement in the classroom and develop inclusive assessments (CAST, 2018). The following are the three principles undergirding the framework:

1. Multiple means of representation: This principle involves anticipating and preparing for in advance any cognitive or physical or perceptual difficulties that students may have in accessing classroom material. Students with learning disabilities, sensory disabilities or cultural and language differences require different formats to suit their needs. It encourages the presentation of content in a variety of formats including images, audio-video, animations and hands-on activities in addition to the text format. Learners with disabilities will additionally require assistive technologies and devices such as screen readers, automatic page turners, voice recognition programmes or closed captioning devices – to access this content.
2. Multiple means of expression: This principle helps provide students with a variety of ways with which to communicate their learning including through written text, visual or oral presentation, or a group project. This principle recognises different ways in which students plan and execute and express their learning tasks. This will benefit learners who experience language barriers and those with sensory or physical disabilities.
3. Multiple means of engagement: This principle supports teachers to use different strategies to ensure learners are engaged in the learning process. For example, learners with dyslexia are generally able to understand concepts more quickly through experiential learning than through the use of printed texts. Engaging in observation, inquiry, drama, role-play and group activities are some ways of multiple engagement. Teachers have to keep in mind that while some learners prefer spontaneity, others work well where there is a routine, some prefer to work alone, while others thrive in group work.

Integrating UDL and PCK

BOX 7.1 REFLECTION ON A NARRATIVE

Reflect on this narrative.

> 'These students don't understand science … they come from a deprived background!' We frequently hear such opinions expressed about children

from rural or tribal backgrounds. Yet consider what these children know from everyday experience: Janabai lives in a small hamlet in the Sahyadri hills. She helps her parents in their seasonal work of rice and tuar farming. She sometimes accompanies her brother in taking the goats to graze in the bush. She has helped bring up her younger sister. Nowadays she walks 8 km every day to attend the nearest secondary school. Janabai maintains intimate links with her natural environment. She has used different plants as sources of food, medicines, fuel wood, dyes and building materials; she has observed parts of different plants used for household purpose, in religious rituals and in celebrating festivals. She recognizes minute differences between trees, and notices seasonal changes based on shape, size, distribution of leaves and flowers, smells and textures. She can identify about a hundred different types of plants around her, many times more than her biology teacher can – the same teacher who believes Janabai is a poor student.

Can we help Janabai translate her rich understanding into formal concepts of biology? Can we convince her that school biology is not about some abstract world coded in long texts and difficult language: it is about the farm she works on, the animals she knows and takes care of, the woods that she walks through every day? Only then will Janabai truly learn science.

Source: NCERT (2006). Position Paper: National Focus Group on Teaching of Science. *New Delhi: NCERT, p. 14. Accessed from www.ncert.nic.in*

Changing over to an inclusive learning environment is not an event (it does not happen overnight) but is a process. It takes time, effort and teamwork. The primary requirement for this is to value every child which forms the basis for developing a classroom culture of accepting diversity as part of an egalitarian society. Historically, this understanding has evolved from formal schooling for the privileged (prior to mass schooling) to what works for most children (expansion of schooling) to making some adaptations to meet the needs of the marginalised and disadvantaged (universalisation of elementary education), and finally to creating a rich learning environment that allows every child to participate (inclusive education). This shift from making some adaptations to address gaps in learners to creating an inclusive learning environment comes from an understanding that barriers to learning are not inherent in the learners. But these barriers arise when learners interact with inflexible educational materials, tools of assessments and fixed goals (CAST, 2018).

There is evidence which shows that students – both with and without disability – gain substantially in inclusive science classrooms (Lederman & Stefanich, 2006; Basham & Marino, 2013; Katz, 2013; Ok et al., 2016). UDL helps teachers to eliminate or minimise learning barriers which are created by following traditional science teaching practices. Following UDL-inspired pedagogy increases students' social and academic engagement in science classrooms (Katz, 2013), which assists students in overcoming the cognitive challenges of 'border crossings' into science too. While UDL provides a set of theoretical and normative structures for actually bringing in inclusion perspectives in everyday teaching and learning activities, teachers still need to be prepared and educated in some of the ways and strategies that align with UDL principles. In their review of recent research on UDL in education, Ok and colleagues write that

> although UDL holds promise for promoting academic outcomes and access of students with disabilities to the general education curriculum, we believe that educators need skills, experience, and dispositions necessary to modify and adapt the curriculum to meet the needs of all students.
>
> *(Ok et al., 2016: 22)*

Therefore, in the remaining part of the chapter, we discuss some strategies, with examples, that can be used in proactively designing classroom experiences for students using the UDL principles.

ACTIVITY 7.5

Read the following example of a strategy.

One example of effectively involving all children in the class is to use the Think-Ink-Pair-Share-Reflect strategy, which encourages participation even among timid students or those who may feel left out.

- Ask children an open question, such as one that asks them to decide on something or express an idea
- Ask them to THINK about how will they find the answer to the question
- Ask them to write (INK) notes about their ideas
- Ask them to exchange their ideas with a partner (PAIR)
- Ask for volunteers (girls and boys) to SHARE the results of their investigations and discussions with the entire class
- Ask children to look back on the question, the means they used to answer it, and the answers they arrived at.

This strategy ensures that all children have the opportunity to investigate, and discuss their ideas or answers. This is very important. Ask yourself, 'In my classroom, are there children who almost always raise their hands first to answer my question?' The problem is that as soon as these children's hands are raised to answer you, other children stop thinking. They may need a longer amount of time to prepare their answers, or they assume that other children will answer your question. The pair work presented in the teaching method above allows all children to practice correct vocabulary and to express their views with one other person. This exchange builds their confidence and encourages their participation in answering your questions or those asked by their classmates.

Source: UNESCO (2009). Embracing Diversity: Toolkit for Creating Inclusive, Learning-Friendly Environments. *Bangkok: UNESCO, pp 70–71. Accessed from https://unesdoc.unesco.org/ark:/48223/pf0000183995_eng.*

What are the UDL principles that this strategy is based on? Try the strategy in a class and reflect on your experience in terms of who benefitted, who did not and why.

Further Readings

Capp, M. (2017). The effectiveness of universal design for learning: A meta-analysis of literature between 2013 and 2016. *International Journal of Inclusive Education*. https://doi.org/10.1080/13603116.2017.1325074

CAST. (2018). Universal design for learning guidelines version 2.2. http://www.udlguidelines.cast.org

Examples of Inclusive Science Approaches in Practice

In this section, we briefly discuss some examples of inclusive science education where students' cultural knowledge and ways of knowing were acknowledged and used as resources in science classrooms. The disadvantaged groups can include a range of students from rural areas, socially marginalised communities, poor homes, as well as those with learning difficulties and disabilities. Inclusive education seeks to increase not only access and presence but crucially participation and success for all students in education (Booth & Ainscow, 2016). And through these examples, we will be able to see that proper planning and an open and sensitive mind, coupled with requisite knowledge of inclusion, ensure all students can access and engage with school science.

According to popular notions, children who do not perform well at school come from backgrounds where either education is not valued or where the culture and the discourse at home are not contiguous with the culture of schools. This problem becomes severe in the case of science education, for science classrooms are often understood as spaces which have their own ways of talking, being and participating. Students coming from tribal and rural regions, girls, students from low socio-economic backgrounds and lower castes often are at a disadvantage in science classrooms because the formal school curriculum recognises and incorporates the values of a small group of powerful minorities, thus allowing children from those groups to find opportunities for excelling in science. There is sufficient research now that states that the marginalised sections of society have their own 'funds of knowledge' which include the knowledge, competence and skills present in the life experiences of students who are under-represented in science (Rios-Aguilar et al., 2011). When school curriculum and teachers make an effort to activate and mobilise the funds of knowledge of students, their participation in science classrooms improves and they are better able to connect science to their everyday lives.

Barton and Tan (2009) report students' participation in a lesson on 'Food and Nutrition' in which students were asked to bring to class a salad recipe from their homes and interview a family member on that recipe. The students then formed small groups in the class and made salads using the ingredients and the recipes they brought from home. The teacher then utilised this class activity to teach students about different parts of the plants that went into their salads and at the same time instilled the importance of healthy eating among them. The outcome was that mostly girls, and other students who rarely used to participate in science classes, thoroughly enjoyed the salad making activity as they had emotional connections with the recipes and consequently learnt about parts of plants in a fun and engaging manner. The researchers who observed the classes wrote that 'several quiet students who received low grades earlier in the term, centrally participated in the discussion, sharing recipes and talking about how their recipes contained different parts of plants' (Barton & Tan, 2009: 66).

In India, one of the most common notions is that children coming from tribal backgrounds lack the necessary cultural knowledge that would help them make sense of scientific concepts and thus learn science. But several studies have shown that tribal children, owing to their proximity to natural resources, perform better on scientific, academic tasks than their rural and urban counterparts. A series of reports published as part of the project Diagnosing Learning in Primary Science (DLIPS) at the Homi Bhabha Centre for Science Education describes the alternative conceptions of students in rural, tribal and urban regions on different topics in elementary science. The researchers found that tribal students made more correct judgements of distinguishing between living and non-living objects than urban students, defying the popular notion that tribal ways of thinking are more animistic (Chunawala et al., 1996). They write that tribal students were more positive about plants, described a greater variety of plants than urban students and possessed a richer understanding of ecology than what was present in textbooks. The tribal students expressed their rich knowledge of seasonal features of plant life such as time of flowering, sprouting and shedding of leaves, etc. and had a richer grasp of interdependence in the forest ecosystem. When asked to draw pictures of trees and plants, they drew much more realistic pictures of a large variety of trees, often correct in the placement of leaves, fruits and flowers. The researchers argue that since 'in tribal cultures, there is a direct dependence on plants for survival, shelter, food, and medicine', the students learn about aspects of plant life much deeply and organically (Chunawala et al., 1996: 4).

Another example of students from marginalised communities possessing resources for learning school science comes from Padalkar (2010) who conducted a study of students' understanding of astronomical phenomena with rural, tribal and urban students. While overall, students from rural, tribal and urban samples knew textbook facts equally well, rural students were more familiar with indigenous knowledge than urban and tribal students, and tribal students were better in terms of observations of daily astronomical phenomena than their rural and urban counterparts. Padalkar reasons that students in rural and tribal areas in Maharashtra (where her study was situated), worked in farms, had experiences of working in open spaces and handling or estimating (relatively) large areas which could have contributed to their better understanding of certain astronomical phenomena.

In the first section of this chapter, we discussed how language becomes a barrier to students' participation in science. In the context of education of both children and adults, Saxena (2010) writes that when students are provided educational materials in their own language, which could be different from the dominant regional language or language of textbooks, their comprehension and engagement with the material improves. Writing about experiences of both adults and children who belong to the most disadvantaged sections of society and are linguistically removed from the dominant language culture, she shows that when teachers are motivated, active and determined to bring about a positive change, change does occur. Oftentimes, in classrooms students' languages were considered backward, and therefore were ridiculed and undervalued. This resulted in students feeling alienated from the classroom and mostly staying silent. To overcome the language barrier, additional educational materials were prepared in '*Bundeli*' (the mother tongue of most students), the selection of materials was done carefully, the vocabulary was familiar and the selection was made after several trials. The textbook content was drawn from oral resources which were substantial owing to the rich oral culture of the region, in addition to the printed material in Hindi and English. The result was that students started showing more interest in 'reading' the materials on display in schools and their competence in identifying patterns of written text or 'reading' improved in just three months.

Saxena (2010) underscores the significant role of the teacher in reaching out to the most vulnerable students and making efforts to improve their learning. She writes, 'If the teacher was keen, motivated, and ingenious, she made use of various opportunities and enriched the class. On the other hand, reading material was not of great help if the teacher was not motivated' (Saxena, 2010: 147).

Each child is unique and children in a classroom have diverse learning needs. Studies show that many groups of students are placed in a disadvantageous position vis-á-vis science learning (UNESCO, 2019). Teachers who recognise this emphasise the need for inclusive science classrooms (UNESCO, 2017). As mentioned earlier, inclusive education seeks to improve access, presence, participation and success for all students in education (Booth & Ainscow, 2016). While the larger educational system, schools as institutions, curriculum and textbooks all play a critical role in ensuring inclusive education, teachers are key to creating inclusive learning classrooms (NCERT, 2006). An important aspect to remember here is that students possess a rich base of knowledge which is waiting for its proper utilisation in formal educational environments. When interacting with students who do not belong to socially powerful groups, the default perspective of teachers should not be of 'deficit' – that the marginalised students lack something that the others do not. Rather, teachers should view the situation as a challenge to ensure they participate in classroom interactions. Their perspective should also be of a sense of opportunity that they have received to enrich their classes with the experiences of these students.

ACTIVITY 7.6

When it comes to teaching students with disabilities, Ankur Vidyamandir in Pune is an example of schools which are inclusive. The school has a no-rejection policy meaning that any student irrespective of their background, disability, gender, language, caste or class is given admission into the school. The school works with each student to help her/him/them learn and become an independent and productive member of society. They also run a therapy centre which provides different kinds of therapies for the rehabilitation of students who have difficulty when it comes to basic motor and communication skills. Similarly, central government research organisations such as the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune, have engaged with taking astronomical concepts and ideas to visually challenged students. Modules have been created for blind children which introduce maps and map reading to them. For example, in a module on map reading, tactile sensory inputs were given priority over the visual ones used commonly. The boundaries of each continent were made using a different kind of thread. Care was taken that the texture of each thread was different so that students could sense when one continent ends and the other begins. The index on these maps was provided in both Braille and English. The same unit then built upon this knowledge to teach latitude and longitude by placing a tactile grid on top of the map.

Identify an example of an inclusive school and an organisation that supports inclusive science education. Describe some of the strategies they use to promote inclusive learning.

SUMMARY

In this chapter, we learnt:

- There are multiple barriers to participation in STEM. Examples include gender, caste, language, class, disability and geo-political region.

- Students from these socio-economically disadvantaged groups are under-represented in advanced science education and in STEM-related careers.
- It is important to have diversity in science not just from the perspective of social justice but also because diversity helps in the growth of science.
- Initiatives to make science accessible to the general public have existed in the country. Some prominent examples are Hoshangabad Science Teaching Programme, National Curriculum Framework 2005 and DST-INSPIRE Fellowship.
- Teacher preparation is an important factor in ensuring that science education is inclusive and equitable.
- Universal Design for Learning (UDL) is a useful framework which helps in designing educational experiences so that all students are able to participate in and engage with science lessons.
- Flexible planning is an important first step in designing inclusive classrooms.
- Teachers should carefully consider classroom organisation, selection of teaching-learning resources and assessment strategies in their planning process.
- Guided inquiry, project method and nature-based learning are some strategies that promote inclusive learning in science classrooms.

It is important to remember that students from socio-economically and educationally disadvantaged communities also possess a rich knowledge base. Therefore, learning experiences should be designed in a way to activate and utilise their knowledge adequately in science classrooms.

Exercises and Practice Questions

1. Write a concept note in about 500–1,000 words, explaining why diversity among scientists is needed.
2. Describe how organisational cultures affect the science participation of students from non-dominant social groups. Illustrate this using examples from your experience, newspaper/media articles or your own experience.
3. Describe with examples approaches to transact a science topic of your choice, to help students imbibe the values of honesty, integrity and cooperation.
4. Given in Table 7.1 is the analysis of a classroom observation. Suggest ways of structuring learning to overcome each of these problems.

TABLE 7.1 Analysis of Classroom Observations

What was happening	*Possible reasons*
Children not handling materials	Were there enough materials? Did the children realise that they could touch and use them?
Very restricted observing	Were the children really interested in the problem given?
Few questions raised	Was more time needed for children to become absorbed and to realise what sorts of things they can find out through their own actions?
Not much discussion	Were they used to sitting quietly in class and being told most things?

Source: Wynne Harlen and Jos Elstgeest. (1992). *UNESCO sourcebook for science in the primary school. A workshop approach to teacher education*. National Book Trust, India, p. 39.

5. Write a plan for using the natural environment to engage students in a topic of your choice.
6. In order to conduct investigations, students need to be able to identify and operationalise key variables. Based on the following example, prepare a variable table (Table 7.2) for students to use for a research question of your choice.

Example of a research question: How does the amount of light affect the growth of seedlings?

TABLE 7.2 Table of Variables for Students

What I will keep the same?	*What I will change?*	*What I will measure?*
Type of seeds Type of soil Amount of water Amount of fertilizer Size of container Planting depth of seeds	The amount of light: • Dark • Partial shade • Full sun	The height of the seedlings
Controlled variables	Independent variable	Dependent variable

Source: Author.

7. Study frameworks for inclusive schools developed by various agencies such as NCERT, UNICEF and UNESCO. Adopt/adapt them to assess readiness for inclusion of a school where you intern.
8. Design a science lesson using UDL principles. Try it out with a group of students as part of your practicum course and write a reflective report. Share it with your classmates.

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APPENDIX

Resources and Tools for Practice

This section provides brief descriptions, suggestions, resources and tools for getting ready for classroom teaching.

Planning

Several ideas have to be taken into account during the process of planning. Flexible planning is essential to promote meaningful learning. It is important that teachers reflect on the planning process after classroom transactions. The 5E model can be used to design lessons. A number of strategies can be adapted by teachers to address the needs of all children in the science classroom.

As we have discussed earlier, schools aim to develop three kinds of learning in students – conceptual learning, procedural learning and metacognitive skills.

1. Conceptual learning leads to an understanding of the basic concepts and principles of a subject. When learning is based on concepts, it is more meaningful and helps children retain what they learn, instead of them memorising a set of discrete facts.
2. Procedural learning refers to knowing how to do things. In science, this requires developing process skills, which require practice and repeated exposure. To avoid practice being reduced to a meaningless drill, psychologists recommend small doses of practice over longer periods of time. At the same time, they recommend that practice should be supplemented with reflection on why some procedures work (Mukunda, 2009: 43).
3. Metacognitive skills refer to individuals' knowledge of themselves. Helping students think critically is one example of a metacognitive approach to science teaching.

Implied in the UDL framework is the significance of proactive and thorough planning, a necessary first step to creating an inclusive classroom environment. Meeting the learning needs of diverse students necessitates a flexible yet rigorous lesson plan. A well-planned lesson which incorporates multiple means of representation, engagement and expression goes a long way in ensuring that the teacher is confident and prepared to connect with all the students. Planning is an iterative process, and reflection after implementing the plan is key to inclusive education. Research shows that teachers who plan prior to instruction produce higher levels of student achievement (Brophy & Good, 1986).

A plan has three primary components:

- being clear about the needs of students we are teaching and the key ideas of the content or the skills/dispositions we want students to learn.
- deciding how to teach so that all students will understand/develop skills/ dispositions, and maintaining flexibility to respond to the needs of students as they arise.
- reflecting on how well the lesson went and what students have learnt to prepare the next plan.

Planning is a complex process. It links theories of learners and learning, knowledge and curriculum, and pedagogy on the one hand with the larger aims of education and objectives of teaching a specific topic on the other, to actual practice. Classroom practice is not merely a collection of activities that can familiarise students with a topic. It involves the execution of a carefully constructed plan for using a variety of methods and approaches to provide meaningful learning experiences to students. Planning has to be dynamic and flexible; it should respond both to the progress of students' learning and incorporate feedback on the classroom practice. Also, planning should give a teacher an opportunity to take up 'teachable moments' as and when they arise. The process of planning is both difficult and time-consuming in the beginning but is crucial for effective classroom practice.

To get a clearer picture of the process of planning, consider the following questions. You can also use them as checkpoints when you are making your own lesson plans (UNESCO, 2006; Butt, 2006):

- What are we teaching (topic, content)?
- How does the unit/lesson you are going to teach relate to the rest of the science curriculum?
- What has been taught and learnt in the previous units/lessons?
- Why are we teaching this topic (goals/objectives)?
- How are we going to teach it (methods/process)?
- What do the learners already know in relation to this topic (prior learning; pre-testing)?

- What will the learners do during the lesson (activities)?
- How will we organise the class (including physical and social environment)?
- What resources will we use?
- Will activities be appropriate for *all* learners?
- Will the learners have the opportunity to work in pairs or small groups?
- How will learners record what they have been doing (learning products)?
- How will we know what learning has taken place (feedback and assessment)?
- What do we do next (reflection and future planning)?

Since reflection is an essential component of effective planning, once the class is over you can think about the following questions:

- How will you know what students have learnt?
- How will you know how effective the lesson has been from your perspective as a teacher and from the perspectives of students? (assessment)
- What action will you take in your next lesson to ensure that effective learning is taking place? (reflection)

These questions indicate how a number of factors have to be taken into account in the process of planning. We must remember that a unit or a lesson is not an 'event'. Hence, a unit or lesson should **not** be planned in isolation from those that go before and after it. Once we understand the broader picture of the unit/lesson, we can frame the learning objectives, the first part of lesson planning.

Learning objectives are central to a plan and give focus to the teaching-learning process. As we have seen earlier, three types of learning, namely conceptual, procedural and metacognitive skills, are to be developed in schools. So, the learning objectives must include these apart from appropriate attitudes and values. For the former three kinds of learning, the revised Bloom's taxonomy can serve as a guide to formulating learning objectives.

Benjamin Bloom and his colleagues developed a hierarchical taxonomy of educational objectives (Bloom et al., 1956). The taxonomy was later revised to include a cognitive process dimension (Anderson & Krathwohl, 2001). The taxonomy classifies educational objectives into groups on the basis of the cognitive complexity they entail and on the basis of the different levels of cognition that would be required to meet these objectives (Dymoke & Harrison, 2008).

Once we identify the learning objectives, we need to plan for learning experiences to help all students achieve these objectives. The planned experiences should take into account the different needs of students in the classroom. The nature of learning experiences we plan will depend on the current abilities of students, the particular concept/skill to be taken up for teaching, the approaches/methods adopted, resources available and so on. The previous chapters provide us with ideas for designing a variety of learning experiences in different science disciplines.

Once we decide on the learning experiences, we need to plan for classroom organisation and management. The lesson/unit plan should also indicate strategies to revisit the learning objectives and assess how much students have learnt and how well they have developed their understanding and skills. There should be a clear link to the next lesson(s) within a unit.

A plan therefore brings together learning objectives and teaching-learning strategies drawing from a variety of pedagogic approaches and contexts for learning. A plan is not only a framework for teaching but also the starting point for reflection. After every lesson, as a beginner teacher, one must reflect on the experience of the class, using the lesson plan to structure one's reflection around what was planned and the resultant lesson sequence.

BOX A1 TEMPLATES FOR LESSON PLANS

Templates for lesson plans based on UDL principles are given on this website:

https://www.theudlproject.com/udl-tools---all-grades.html
Use one to create a lesson plan. Share it with a friend for feedback.

Resources

Resources are crucial for teaching and learning about the natural world. While a basic school laboratory is necessary for secondary school science, locally available materials can be used to teach many science concepts. It is important to remember that one set of resources will not be sufficient to cater to the needs of all learners. A teacher should prepare a variety of resources which enable multiple forms of representation and expression. In fact, knowledge of various resources and their use forms an important aspect of the pedagogical content knowledge (PCK) of teachers (Sarangapani, 2016).

A learning resource should cater to the needs of learners in a given context. Learning resources can be broadly classified based on several criteria such as:

- Manner in which they are used: Tools, manipulates, as audio-visuals, instructional materials, as raw materials to make something else out of them.
- Kind of activity: Movement, observation, display, demonstration, exploration, narration, experimentation, evaluation and assessment.
- Nature of activity: Collective group activity, small-group activity, pair work, individual activity.
- Mediation: Facilitated by the teacher or self-learning.

A range of resources can be effectively used to help students learn an investigative and exploratory subject like science. These can include nature walks, field trips, live specimens, toy making, model making, drawing and illustrations, learning games, books, worksheets, websites, apps and so on. Learning resources are not always in the form of material, tangible objects. Intangible resources like student-talk are valuable resources and crucial to learning in science. Discussions between students and between teachers and students must be central to all science learning. To ensure meaningful use of a wide variety of resources, it is important for a teacher to plan well. Collaboration with other teachers and/ or nearby teacher education institutes will help maximise the use of available resources and provide an opportunity to get into a mutual exchange of learning. Furthermore, involving students in both finding and creating resources will ensure greater involvement and learning for them. Learning resources can cater to the diverse needs of learners by using the UDL principles of multiple representations, expression and engagement. Here is an example:

BOX A2 MAP MAKING

Subject: Integrated learning of science, social science and mathematics
Suggested levels: Grades 6–7   Topic: Map making
Purpose: Representation, demonstrating conceptual understanding of ratio and proportion, scale, approximation, direction and measuring distance.
Instructions:
Make groups of four to five.
Ask students to take a walk in groups around the school to some important place in the neighbourhood – for example, a nearby tree, place of worship, flag post, bus stand, garden, etc. Ensure that they make a few turns and pass by roads to reach this place. Ensure students' safety when they go out. Let them observe and note important places or things (a tree, compound wall, etc.) on their route. Students should keep a track of the route that was taken to go and come back. Let them draw a map of the route with approximate distance marking and labelling important landmarks. Alternatively, if students cannot go out during school hours, they can make a map of the school campus.

To teach scaling: Draw different objects on a graph sheet which has 1 sq cm grids. Let them draw grids in a sheet of paper of sizes 2 sq cm, 5 sq cm, etc. Ask students to draw the same objects in these grids of different sizes, ensuring the dimensions are proportionate. Children then use a similar grid sheet to redraw their map with different scale.

Ensure every student irrespective of her/his/their abilities contributes to the process.

Encouraging students to use other sensory cues such as smell, slope of road, noise, number of steps taken, etc. can also support students who have visual impairment. For this purpose it would be useful to stretch the activity to be explored for a week so that students will get used to the route and form cues. These cues are to be mentioned in the map along with other labels. The labels can be made in Braille, if the teacher/students know the language, or sticks, thick cardboard pieces and other materials that protrude can be used for map making.

Opportunities can be given for students to describe the map making process through mime or sign language, where the teacher/student knows the language.

Source: DSERT-RVEC-SIA Resource Booklets for Inclusive Education. Retrieved from: https://karnatakaeducation.org.in/KOER/en/index.php/Portal:Inclusive_Education

Textbooks

A textbook is a key resource in a classroom. Given its ubiquity, we often take it for granted. As teachers, though, we must be able to critically analyse a textbook for its suitability to our learners and their context. Here are a few aspects to be considered while analysing a textbook. Criteria for analysis are suggested for each aspect.

1. Language
   - Is it student-friendly?
   - Is the vocabulary appropriate for the targeted reader? If not, (how) can the teacher help the reader make sense of the text? Looking at textbooks of several publishers (for the same concept) can give an idea to the teacher of how it can be dealt with in various styles.
   - Is it free of biases and does not promote stereotypes?

BOX A3 EXAMPLE OF PERPETUATION OF STEREOTYPES FROM A STUDY OF SCIENCE TEXTBOOKS

Here is an example of how stereotypes are perpetuated, from a study of science textbooks for grades 3 to 10 done by Homi Bhabha Centre for Science Education.

> The analysis of textbooks revealed that the schools texts continue to present gender biases by omission and commission. Not only are there significantly fewer female figures, these figures are also not active but were often passive observers. Besides, females were depicted in stereotypical images (mother, nurse, teacher, etc.) and in non-remunerative occupations limited to the domestic space. On the other hand, men were portrayed in a variety of activities, which were economic in nature. Nowhere in the texts

were women depicted as developers of history and initiators of events in S&T – neither were actual women scientists depicted nor was the possibility of women scientists explored. What example does this set for a girl who has a dream to become a scientist (or does she even dream thus?) and for a boy who wants to be an elementary school teacher? Also there was a bias in the language with use of terms like 'mankind', 'manmade', etc.

Source: http://www.hbcse.tifr.res.in/research-development/gst

2. Illustrations

   Illustrations need to be scrutinised for clarity, appropriateness, presentation, quality and attractiveness.

   Science education researchers Vinisha and Ramdas (2013) argue for the critical importance of visuals and text to be appropriately integrated within the textbook, in order to allow effective communication.

3. Content

   The subject matter content in textbooks should be analysed according to the following considerations:

   - key concepts.
   - evidence-based arguments in support of key concepts.
   - coherence among key ideas, between key ideas and their prerequisites.
   - accuracy, including factual errors, misleading statements, statements that may reinforce commonly held alternative conceptions.

4. Quality of pedagogic support.

   A textbook must provide a sense of purpose both to teachers and learners. It must allow taking into account students' prior ideas and enable them to develop and use scientific ideas presented. Alongside engaging students with scientific concepts, a textbook must promote studying natural phenomena and scientific knowledge. A well-written textbook lends itself to a range of pedagogic practices and contextual adaptation by a teacher. While analysing a textbook, one must keep in mind that oversimplification can result in a loss of rigour. A good textbook is able to balance access and relevance for learners with the depth of treatment that concepts require. Exercises that appear at the end of each chapter are excellent avenues for allowing sustained learning of science by the student both individually and collaboratively within and outside classrooms. Textbooks can provide tasks that promote working with simple, everyday items to reinforce the concepts taught in the lesson.

5. As we saw in the second chapter, providing biographies of scientists allows capturing the idea that science is a human endeavour. This is often missing in most science textbooks. Stories of important discovery or a path-breaking invention by diverse peoples, the struggles of individual and groups of scientists and so on can inspire students.

Other factors, like the general layout of the book, the price, paper and quality of print are of course necessary items in any checklist for textbook analysis.

ACTIVITY

Compare the science textbooks of any one class from different publishers, using the above-mentioned criteria and adding more of your own. Discuss your comparison with the rest of the class. How do your views differ? Where do you agree? Why?

For any one topic, think of measures you will take to improve the textbooks to meet the needs of a group of learners.

Organising an Inclusive Classroom

Well-organised classrooms set the stage for teaching and learning. They help to motivate children, enhance learning, prevent behaviour problems and create a conducive learning environment. Every grade has diverse groups of children and a teacher therefore needs to organise the classroom space flexibly to meet the needs of all children. A teacher has to ensure learners with disabilities can enter and move around the classroom easily; s/he has to take into account students who will need extra help and the kind of support they will need in terms of seating arrangements and resources.

Classrooms are to be used for a wide variety of activities. The flexibility to accommodate both large-group and small-group activities and to adjust the room to meet the needs of the particular activity is an advantage. When students are to work in groups they need to interact, share resources and so on, and seating arrangement will be important. Care should be taken not to create areas where students cannot be easily observed.

Active learning can be promoted through cooperative and collaborative learning. The underlying premise for both collaborative and cooperative learning is founded in constructivist learning theories. Both involve students working together in small groups, learning tasks that are designed for group work, emphasis on interdependence while maintaining individual accountability and participation, the teacher in a facilitative role. While cooperative and collaborative learning are generally used interchangeably, there are differences between them. Cooperative learning is an organised and structured way to use small groups to enhance student learning and interdependence. Students are given a task and they work together to accomplish this task with each student assigned a specific role. Success is dependent on the work of everyone in the group. It is more directive and teacher-driven and emphasises the development of cognitive, personal and social skills. Collaboration is more a philosophy of interaction and happens when students have experience of working in groups. Students take responsibility for their actions, including learning and respecting the abilities and contributions of their peers. Collaborative learning is more student-centred and focuses on the development of autonomy and knowledge construction.

Display of students' work is important. Creative and interesting display boards made from local materials, such as mats or old cardboard boxes would be handy in displaying students' works. They would be good teaching-learning resources and provide a lively focus in the classroom. Displaying students' work would also improve their self-esteem and give them an opportunity to learn from each other (UNESCO, 2010).

School and the classrooms must be exciting and stimulating places in which to learn. Even if learning materials are scarce and furniture is poor, the school and classroom space can be well ordered, clean and made interesting with some creative thought. Every student should feel a sense of belonging. Students can be encouraged to participate fully in organising and managing the school, their classroom and learning materials. This will help them develop responsibility and a sense of ownership.

Assessment

Assessment forms a critical component of the teaching-learning process. It is elaborated in Chapter 6. This section briefly outlines a few key principles to ensure assessment does not create barriers to learning.

Assessment is a way of observing, collecting information and then making decisions based on that information. Tools and strategies used for assessment need to be diverse as well. We saw in the first section that one of the UDL principles is multiple means of expression. Therefore students must demonstrate their learning not just through written tests but also through, for example, discussions, presentations, role-plays, stories, artwork, model making, performance art and so on. Additionally, students with disabilities require accommodations in assessment. These may include

> an architecturally accessible testing site, a distraction free space, an alternative location, test schedule variation, extended time, the use of a scribe, sign language interpreter, readers, adaptive equipment, adaptive communication devices, and modifications of the test presentation and/or response format.
>
> *(Thurlow et al., 1993, quoted in Lederman & Stefanich, 2006: 71)*

Portfolios offer a rich means of displaying the learning of all students over a period of time. A portfolio is a representative collection of an individual student's work, which indicates what they have done and learnt. It is an ongoing assessment strategy allowing both the teacher and student to track a student's progress throughout the year. Students must be encouraged to develop their own portfolios so they are able to represent their own efforts and accomplishments in a concrete form. Portfolios can also include a student's own proposal indicating his/her/their instructional goals, learning interests and performance on a variety of learning tasks (Lederman & Stefanich, 2006).

A range of options is suggested in the following box to allow students to display evidence of their learning. Include at least four of them in your unit plan and try it out with a small group of students.

BOX A4 FORMS OF EVIDENCE

Oral evidence	*Written evidence*	*Graphical evidence*	*Products*
Questioning	Questionnaires	Diagrams	Models
Listening	Diaries	Sketches	Artefacts
Discussing	Reports	Drawings	Games
Presentation	Essays	Graphs	Photographs
Interviewing	Notes	Printouts	Databases
Debates	Stories	Overlays	Dance performances
Audio recording	Newspaper articles	Video clips	Puppet shows
Video recording	Scripts	Spreadsheets	Plays
Role-play	Short answers to questions	Computer presentations	Exhibitions
	Lists	Storyboards	
	Poems		
	Descriptions		
	Portfolios		
	Booklets		

Source: Compiled by authors from various sources.

Feedback is also important in communicating what we have assessed. Characteristics of effective feedback include (UNESCO, 2005):

- focusing on the task and being given regularly while it is still relevant.
- providing clear guidance for the correction of errors or other improvements in a piece of work.
- scaffolding children's further learning, that is, children should be given as much help as possible in using their knowledge. They should not be given the complete solutions as soon as they have difficulties. They should be helped to think things through for themselves often in a step-by-step manner.

Assessment and subsequent feedback have to ensure the holistic development of children. Also, in an inclusive classroom, a teacher has to maintain a balance between having high expectations from *all* children and at the same time not pushing children too much that they lose self-confidence. This means that:

- A teacher has to have high expectations from students. Studies have conclusively shown that students' performance is directly linked to their teachers' expectations from them (Bransford et al., 2000).
- It is essential to identify individual learning gains (as against achievement with respect to standard outcomes) of each student to promote self-esteem and the drive to learn.
- At the same time, it is important to provide additional support and resources to help a child learn to her potential.

Further Reading

This manual gives a number of illustrated ideas to organise school and classroom space creatively for learning.

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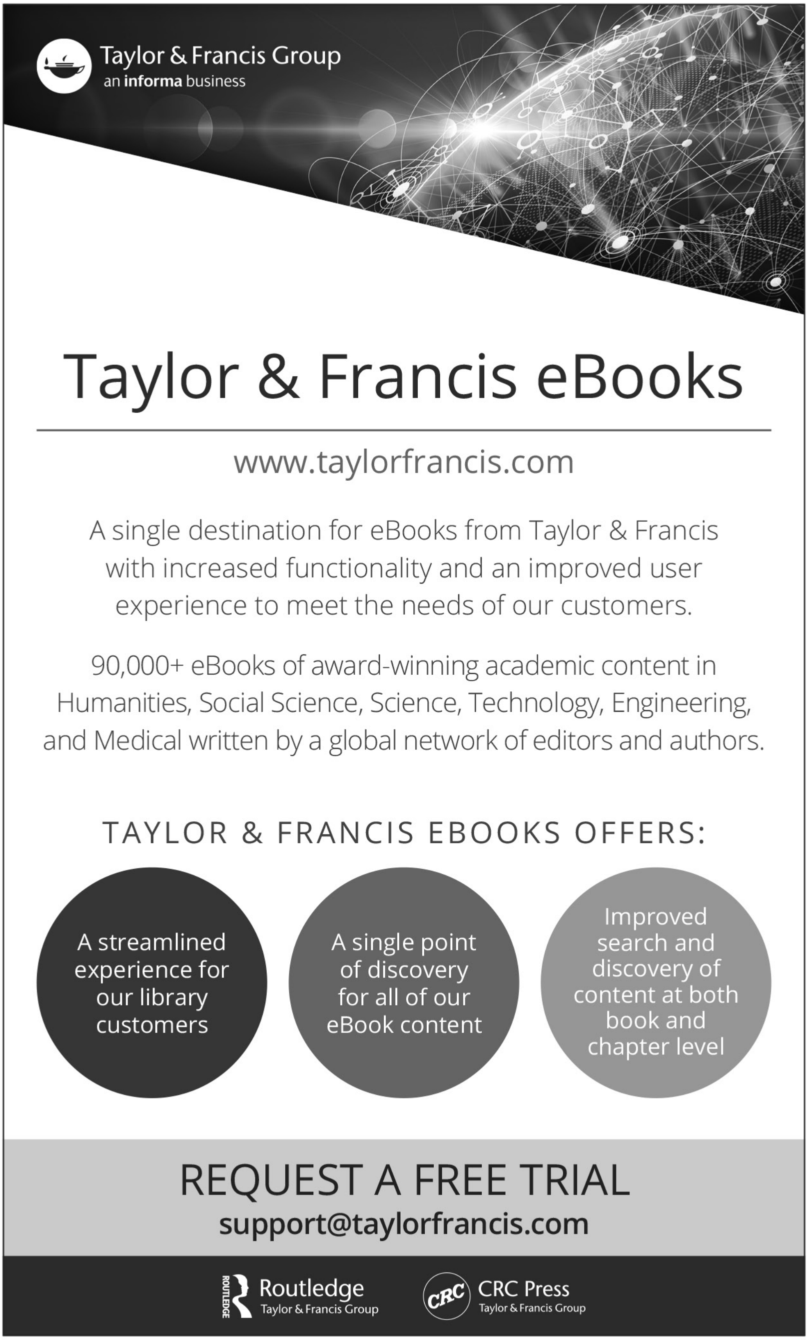
Page numbers in **bold reference tables.
**Page numbers in *italics* reference figures.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