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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Principles-Based Adaptive Teaching

Series Editors: **Mythili Ramchand** and **Nishevita Jayendran**, *Tata Institute of Social Sciences, Mumbai, India*

This series bring together critical discussions of educational practices and pedagogies in India. The teaching profession has undergone rapid changes and advancements in recent years. The books in this series will identify the changes which are affecting teaching-learning practices in schools and the range of knowledge development required for educators to develop and adopt innovative pedagogical practices to adapt to uncertain futures. The books in the series include worksheets, vignettes, emerging classroom discussions, case studies along with other additional resources for teachers and students. The series caters to a range of teacher education programmes and the volumes are envisioned as resources, primarily for teacher educators and student-teachers and others engaged in the education sector. It focuses on topics such as adolescence in India, pedagogy of language (English), pedagogy of mathematics and pedagogy of science, the nature and purpose of education, philosophy of education, knowledge and curriculum, learners and learning, educational policies and practices, teachers and teaching, inclusive education, pedagogies of language, social sciences and assessments and evaluation, within the themes of education.

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SCIENCE EDUCATION

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

CONTENTS

List of Figures, Tables, Boxes *x*
Series Editors' Note *xii*
Foreword *xv*
Acknowledgements *xvii*
Abbreviations *xviii*

Introduction 1

1 Science Education: An Overview 7

2 Nature of Science 26

3 A Cognitive Approach to Learning Physics 56

4 An Inquiry-Based Approach to Learning Chemistry 91

5 A Socio-cultural Approach to Learning Biology 115

6 Assessment in Science Education 134

7 Inclusive Science Education 158

Appendix: Resources and Tools for Practice *183*
Index *194*

FIGURES, TABLES, BOXES

Figures

0.1 Pedagogical content knowledge is the kind of knowledge teachers need to possess in order to teach their specific subject effectively 3
2.1 Observation or inference 53
3.1 Wondrous universe, inside and out! 58
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.) 69
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)? 75
3.4 Incorrect shape of gibbous moon drawn by a student (recreated for printing purposes) 81
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) 85
4.1 Inquiry begins with systematic observation 92
5.1 Nature and nurture, inextricably intertwined 117
5.2 A commonly used but incorrect depiction of evolution 125
5.3 Darwin's finches by Gould 128
5.4 Artistic drawing showing evolution of peppered moths 130

Tables

2.1 Brief Description of the Elements of Scientific Knowledge 34
3.1 Grade-Wise Syllabus for Two Topics in Physics 62
4.1 Grade-Wise Syllabus for Chemistry 112
6.1 Example of a Blueprint for a Unit Test for Grade 9 Based on the Maharashtra State Board Curriculum 145
6.2 Blueprint of the Questionnaire to Assess High School Students' Knowledge in the Area of Astronomy 156
7.1 Analysis of Classroom Observations 179
7.2 Table of Variables for Students 179

Boxes

1.1 Reflection on 'Show and Tell' Approach to Science Experiments in Classrooms 19
2.1 Reflection on the Nature of Scientific Knowledge and Methods of Science 28
2.2 Anecdotes from Science 29
2.3 Evolutionary Aspect of Scientific Knowledge 30
2.4 Reflection on Inquiry 38
2.5 Report on How Youth from Rural Areas and Traditionally Marginalised Castes Miss out on Higher Education and Pursuing Science in India 39
2.6 Large-Scale Science 41
2.7 Brief Sketch of Three Scientists from Different Times and Countries 42
3.1 Example of Guided Inquiry 64
3.2 Socio-cultural Approaches in Physics Education 66
6.1 Anand Niketan Philosophy 139
6.2 Examples of Formative Assessment 141
6.3 Revised Bloom's Taxonomy of Cognitive Domain 143
7.1 Reflection on a Narrative 171
A1 Templates for Lesson Plans 186
A2 Map Making 187
A3 Example of Perpetuation of Stereotypes from a Study of Science Textbooks 188
A4 Forms of Evidence 192

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

Chairperson, Centre of Excellence in Teacher Education (formerly, CEIAR), India

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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.

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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

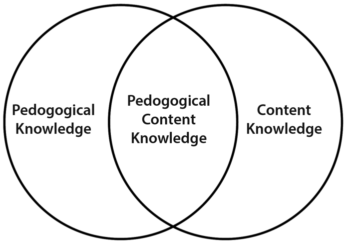

FIGURE 0.1 Pedagogical content knowledge is the kind of knowledge teachers need to possess in order to teach their specific subject effectively. Source: Illustration by Ramesh Prakash Khade.

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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Introduction

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Inclusive Science Education

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