Chapter 8
Science Teacher Education for the Changing Landscape

Jon Sien Darren Wong, Kim Chwee Daniel Tan, Yew Jin Lee and Tuck Lee Augustine Tan

8.1 Preparing Teachers to Teach Science

Teaching has become increasingly complex and multifaceted against the backdrop of changing demands in society. More than ever, learning and teaching has to take into consideration Schwab's (1969) four "commonplaces of education" where the teacher, learners, subject matter and milieu (or context) are in dynamic and constant interaction. A teacher is not simply a conduit to deliver a planned teacher-proof curriculum but plays an inextricable part during curriculum development, implementation and evaluation. The nigh unteachable "problematic" way in which a teacher actively makes pedagogical decisions in response to the particular and varied learning demands of the situation is well known:

> Teachers' active decision making and the reasoning that directs and informs their practice has a great deal to do with the ways in which teaching and learning experiences unfold in the practice setting. Hence, from a teacher thinking perspective, teaching is problematic. There is no one way to teach a subject and no one way that all students learn that subject. There are multiple decision points that need to be negotiated by both teacher and learner, hence teaching is problematic. (Loughran 2013, p. 120)

J.S.D. Wong (✉)
Ministry of Education, 1 North Bouna Vista Drive, Singapore 138675, Singapore
e-mail: darren_wong@moe.gov.sg

K.C.D. Tan · Y.-J. Lee
Natural Sciences and Science Education, National Institute of Education,
1 Nanyang Walk, Singapore 637616, Singapore
e-mail: daniel.tan@nie.edu.sg

Y.-J. Lee
e-mail: yewjin.lee@nie.edu.sg

T.L.A. Tan
Office of Faculty Affairs, 1 Nanyang Walk, Singapore 637616, Singapore
e-mail: augustine.tan@nie.edu.sg

O.-S. Tan et al. (eds.), *Teacher Education in the 21st Century*,
DOI 10.1007/978-981-10-3386-5_8

In making these informed though often implicit decisions about practice, a teacher would be tapping on an elaborate knowledge base, a central piece of which is the teacher's pedagogical content knowledge (PCK), as first coined by Shulman (1986, 1987). While skilful performance may be honed through experience, there is a need to help educate teachers to reason soundly about their teaching—equally across successful as well as less than spectacular episodes. Teachers would need to not only know what to do but also why they do what they do; that is, to learn to provide defensible grounds for choices and actions from their accumulated knowledge base (Morris and Hiebert 2011). Teachers gain a better understanding of the learning–teaching relationship by reflecting on the judgments and actions made in teaching, and linking these to student outcomes such that they learn how to teach particular content in productive ways over time to enhance understanding. This is in line with Clarke and Hollingsworth's (2002) model of teacher professional growth which suggests that change occurs through the mediating processes of "reflection" and "enactment", in four distinct domains which encompass the teacher's world: the personal domain (teacher knowledge, beliefs and attitudes), the domain of practice (professional experimentation), the domain of consequence (salient outcomes) and the external domain (sources of information, stimulus or support).

In this chapter, we begin by reviewing briefly the changing landscape of science education over the past decades from content-focused "science for the scientist" modes to the current emphasis on developing scientific literacy for all students. This will help us gain a better understanding of reforms in science education that inevitably influence what good science teaching means at different periods. A fundamental question, of course, is what knowledge science teachers require to be effective in their profession. However, across international science education communities, there exists no consistent description of proficiency in science teaching, partly as a result of the difficulty in defining proficiency, and partly as a reflection of how complex science teaching is as a research field. As a result, there is a great variance between science teacher preparation programs. This great variance also leads to difficulty in understanding how national systems can be organised to support meaningful science teaching (Darling-Hammond et al. 2005), which is the concern of this paper that describes one such system from Singapore.

We next review the literature on science teachers' knowledge base, especially the concept of PCK and use this as a lens to discuss the implications for science teacher education. What working models of PCK might help us conceptualise the design of teacher preparation programmes? What would be an optimal (if at all possible) mix of content instruction and pedagogy in preparing prospective teachers? How do we nurture teachers to be reflective practitioners, and to help them develop their PCK through professional development and reflective practice? These are some of the questions that are uppermost in our minds. We adapt a model of PCK for science teaching, drawn from literature, which we use as a conceptual framework to frame our approach in developing science teachers' PCK in the NIE, especially for initial teacher preparation.

8.2 Changing Landscape for Science Education

The focus on what it means to prepare teachers to teach science will be affected in part by the concomitant emphasis of science education policy and reform movements at the local and international levels. It will be instructive to review how the emphasis of science education has evolved in the USA and Singapore through the past decades.

Pea and Collins (2008) identified four waves of reform over the past half-century in America, with each wave contributing to new insights on what was necessary to achieve desirable outcomes for science education. The first wave (1950–1960s) began in response to Sputnik, which led to the development of challenging new science curricula with the main emphasis on the mastery of structured subject matter and on the development of scientific inquiry skills. The second wave (1970–1980s) was characterised by cognitive science studies of learners' reasoning in the context of science education, with emphasis on examining novice and expert reasoning differences, resulting in a promotion of strategies such as confronting misconceptions and providing bridging analogies. The third wave (in the late 1980s–1990s) involved the creation of national and state standards, to specify what students should know and be able to do at particular grade levels in specific subject domains. The fourth wave (2000 onwards) involves the emergence of a systemic approach to designing learning environments for advancing coherent understanding of science subject matter by all learners.

However, in Singapore, changes and demands in the economic, political and social landscape often act as precursors to changes and innovations in the educational arena, which subsequently impacts science education. Singapore has consistently transformed its education system in tandem with our nation's economic development since independence in three phases (Boon and Gopinathan 2006): (1) *survival-driven phase* (1965–1978), (2) *efficiency-driven phase* (1979–1996) and (3) *ability-driven phase* (1997–current). Through the 1960s, the focus was on nation building. There was a large-scale recruitment of teachers and a rapid expansion of school places, with a focus on giving every child basic literacy and numeracy skills. A strong emphasis was placed on mathematics, science and technical education so as to produce a labour force with the requisite skills for the industry.

By the end of the 1970s, Singapore had grown to become a newly industrialised nation. There was, however, a relatively high attrition rate in school, with an increasing gap between labour market needs and school leaver skills. To support the drive towards sustainable development and economic restructuring, a New Education System (NES) was introduced in 1979, with the emphasis on efficiency, aimed at reducing educational wastage and meeting the economic demands of the time. In line with the changes in the NES, the science syllabuses at all levels were revised to cater more effectively to the differences in ability and aptitude of students and to provide a broader secondary-school science curriculum. For example, the "S" paper was introduced at the A-Levels for each of the three science disciplines (biology, chemistry and physics) that consisted of higher-order thinking questions to stretch the students with greater ability in the subject. Given the continuing drive to upgrade the nation's workforce to meet the increased demands for knowledge workers, the science syllabuses of all levels were subsequently revised in 1990. Less emphasis was placed on descriptive and factual recall, and greater emphasis was placed on understanding, application, processes and skills. The first two phases of Singapore's education system can be seen to be broadly similar to the first two waves of science education reform in the USA in that both systems were grappling with the same issues of helping students to achieve content mastery, conceptual understanding and process skills in science.

The next milestone towards educational reform was a shift from an efficiency-driven education to an ability-driven one, initiated in 1997 and encapsulated in the vision, *Thinking Schools, Learning Nation* (TSLN). The transition to a knowledge-based economy (KBE) shifts the emphasis of value away from production towards innovation and creativity. The *Teach Less, Learn More* (TLLM) movement launched in 2005 continues the TSLN journey by engaging students more deeply in learning. Schools were given greater ownership and flexibility to develop customised school-based curriculum and programmes to better meet the needs and aptitudes of their students. For science, the emphasis was on authentic and inquiry-based learning in the curriculum. Instead of the traditional one-off examination of practical skills, the School-based Science Practical Assessment (SPA) was implemented in 2004 at the A-Levels (grades 11–12) and in 2007 at the O-Levels (grades 9–10) with the aim of strengthening the teaching and learning of science as an inquiry process and allowing for greater flexibility in the design and choice of practical tasks. The implementation of the First IT Masterplan (1997–2002) saw the provision of data loggers to schools at all levels by the Ministry of Education (MOE) to facilitate science learning and experimentation. To support schools with the TLLM initiative, additional funding was given to schools to develop, implement and evaluate innovative school-based pedagogical practices and curricular resources. This has encouraged a host of school-based curriculum innovations with a focus on inquiry and engaged learning in science (MOE 2008). Examples include teaching investigative questions to students with the aim to develop higher-order process skills, pedagogical approaches that help the less academically inclined students to develop a passion in science and outdoor learning in science using electronic handheld devices.

In line with these changes, the National Institute of Education (NIE) has reviewed its initial teacher preparation programmes to meet the objectives of TSLN. NIE has to ensure that its pre-service curriculum and professional development programmes stay relevant and responsive. In 2009, the new NIE Teacher Education Model for the twenty-first century (TE^{21}) was launched (NIE 2009; for more details, see Chap. 1), after reviewing how NIE's teacher education programmes can be enhanced to equip them to meet the needs of the twenty-first-century learners, with the focus on nurturing the whole child. In tandem, the science education courses were also revised to focus on the development of scientific literacy competencies that students need to take their places in society. Underpinning the TE^{21}

Model is a value-based philosophy of teacher education which guides the design, delivery and enhancement of NIE's teacher education programmes and courses. In particular, TE^{21} adopts a framework of values, skills and knowledge (V^3SK) that focuses on three value paradigms::[1] (1) Learner-centred, (2) Teacher Identity and (3) Service to the Profession and Community, as well as the skills and knowledge teachers must possess to be ready for the twenty-first-century classroom.

8.3 Science Teachers' Knowledge Base and Review of PCK

Since the second half of the 1980s, scholars and policymakers had asked: what knowledge do teachers require to be effective in their profession? The answer to this question has been predominantly influenced by Shulman's (1986, 1987) two seminal articles about teacher knowledge, where he introduced seven domains of teacher knowledge, including the notion of PCK as the special amalgam of content and pedagogy that is part of the professional knowledge base unique to teachers. Shulman (1987, p. 8) further described PCK as representing the "blending of content and pedagogy into an understanding of how particular topics, problems, or issues are organised, represented, and adapted to the diverse interests and abilities of learners, and presented for instruction". To Shulman, how the teacher transforms his or her subject matter knowledge (SMK) into ways that learners can understand is at the heart of teaching.

Since then, there have been numerous studies and reviews on teacher knowledge (e.g. Abell 2008; Cochran 1993; Corrigan et al. 2011; De Jong 2009; Fischer et al. 2012; Gess-Newsome and Lederman 1999; Grossman 1990; Kind 2009; Loughran et al. 2008; Magnusson et al. 1999; Tamir 1988; Verloop et al. 2001), with PCK examined as one of the central domains of a teacher's knowledge base, but with varied interpretations of what PCK actually constitutes and its relationship with the other knowledge domains.

Despite the different conceptualisations about PCK among different researchers, certain aspects of PCK development in science teacher education are generally well established. Firstly, there is no dispute that teachers need to understand the subject matter that they are teaching. Adequate SMK is a necessary precondition (though not sufficient) for developing effective PCK. However, having a Bachelor's degree

[1]As stated by Low et al. (2009): (1) *Learner-centred values* put the learner at the centre of teachers' work by being aware of learner development and diversity, believing that all youths can learn, caring for the learner, striving for scholarship in content teaching, knowing how people learn best and learning to design the best learning environment possible. (2) *Teacher identity values* refer to having high standards and strong drive to learn in view of the rapid changes in the education milieu, to be responsive to student needs. (3) *The values of service to the profession and community* focus on teachers' commitment to their profession through active collaborations and striving to become better practitioners to benefit the teaching community.

in science does not necessarily imply that a student teacher will possess “good” SMK to teach science well. In fact, SMK of student teachers is often vague and fragmented even after having completed their academic studies, especially at the start of their teacher preparation programmes (Gess-Newsome and Lederman 1993). The question that remains is to what extent academic SMK is necessary for effective science teaching. When teachers transform SMK to useful PCK, what knowledge is actually being transformed?

Deng (2007) argues that secondary-school science teaching has more to do with the teacher’s understanding of a particular secondary-school science subject than with his or her knowledge of the related academic discipline. However, a secondary-school science teacher needs to know beyond the content of the school subject; he or she needs to have knowledge of the related academic discipline which is critical to enhancing and broadening his or her understanding of the school subject. He pointed out that it is the subject matter knowledge of school science, often embodied in curriculum materials, which includes knowing several intersecting dimensions: the logical, the psychological, the epistemological and the sociocultural, that the teacher transforms when creating powerful learning experiences for their students in particular classrooms.

Secondly, PCK is discipline specific. Shulman in his original conception defined PCK as topic-specific knowledge for teaching a particular subject. Veal and MaKinster (1999) presented a taxonomy of PCK comprising three levels of specificity. At the top level is general PCK or discipline-specific PCK which is related to science as a discipline. Domain-specific PCK is connected to different domains within science, such as chemistry, biology and physics. At the bottom level is topic-specific PCK which is relevant to a list of concepts, terms and topics in each domain. It has been suggested that student teachers’ PCK mainly includes the lower levels of PCK, while experienced teachers’ PCK also includes the highest levels of PCK.

Thirdly, PCK develops over time as a result of experiences within teacher education programmes, classroom experience and professional development opportunities, coupled with reflection and mentoring (Appleton 2008) to support PCK development. The important role of reflection as part of professional practice has been emphasised by Schön (1983), where he described two levels of reflection: reflection-in-action (during teaching, sometimes described as “thinking on our feet”) and reflection-on-action (thinking back on teaching, to explore what worked, and what did not work, and why, etc.). The important role that school-based mentors play in developing student teachers was investigated by Luft et al. (2003), who found that an experienced mentor has a positive impact on development of the student teacher in progressing towards becoming an independent classroom practitioner more rapidly.

Grossman (1990) highlighted the relationship among three knowledge domains that influence a teacher’s PCK: (1) subject matter knowledge (SMK), (2) general pedagogical knowledge (GPK) and (3) knowledge about context or hereinafter referred to as general contextual knowledge (GCK). According to Grossman, PCK is knowledge that is transformed from these three knowledge domains and is more powerful than its constituent parts. Grossman's PCK model includes four components. The first overarching component is the conceptions of purposes for teaching subject matter, and the other three components are knowledge of students' understandings, curricular knowledge and knowledge of instructional strategies. In developing their model of science teaching, Magnusson et al. (1999) built on Grossman's (1990) model and added a fifth PCK component, namely the knowledge of assessment. The component of knowledge of assessment includes knowledge of the dimensions of science learning that are important to assess and knowledge of the methods by which learning can be assessed. Assessment is not an afterthought but teachers use assessment methods throughout the instructional process to find out what students know, still do not know or have learned, and will adjust their instructional strategies accordingly. Recent moves in the UK towards assessment for learning (Black et al. 2003) make this integral to teachers' instructional strategies. More recently, Park and Oliver (2008) built on the model by Magnusson et al. (1999) but with the components of PCK placed in a hexagonal form to emphasise the interrelatedness among the components. They added a sixth component: teacher efficacy, which they termed as "an affective affiliate of PCK" (p. 270). PCK is to them as integration of the different knowledge components, with the development of PCK facilitated by reflection-in-action and reflection-on-action, as described by Schön (1983).

A way of conceptualising PCK is to view it as being situated within a continuum of models of teacher knowledge, as proposed by Gess-Newsome and Lederman (1999):

> At one extreme, PCK does not exist and teacher knowledge can be most readily explained by the intersection of three constructs: subject matter, pedagogy and context. Teaching, then, is the act of integrating knowledge across these three domains. For convenience, I will call this the Integrative model. At the other extreme, PCK is the synthesis of all knowledge needed in order to be an effective teacher. In this case, PCK is the transformation of subject matter, pedagogical, and contextual knowledge into a unique form – the *only* form of knowledge that impacts teaching practice. I will call this the Transformative model. (p. 10)

In the integrative model, PCK is the result of the intersection of SMK, GPK and GCK in which the constituent parts retain their identities (PCK as a *mixture*). In the transformative model, PCK is the result of the synthesis of these three domains of teacher knowledge which results in new knowledge (PCK as a *compound*). These extremes have implications for science teaching and science teacher education. From an integrative perspective, an expert teacher will select information from a set of knowledge base components in deciding what and how to teach students in a specific context. These components are organised such that they can be drawn on with flexibility and accessed readily. Gess-Newsome and Lederman (1999) noted: "When observing an expert teacher, the movement from one knowledge base to the next will be seamless, giving the appearance of a single knowledge base for teaching" (p. 11). However, integrative models lack explanatory power as no mechanism is suggested that shows how the interaction between SMK, GPK and GCK results in PCK (Kind 2009). Transformative models, on the other hand, imply a mechanism exists where a highly skilled teacher draws on SMK, GPK and GCK to create PCK for instructing students. With particular regard to the SMK–PCK interaction, the teacher could be doing one or more of the following: (1) converting SMK to PCK, (2) using SMK to create PCK or (3) adapting SMK for school use. If we are able to distil such a teacher's PCK and find out how this develops, it might perhaps give hints about the process of gaining it, which can then provide student teachers and beginning teachers with explicit strategies of combining material from different sources in order to teach a particular topic.

8.4 Developing Science Teachers' PCK at NIE

The model of PCK for science teaching that we will use to frame our description of initial teacher preparation programme is adapted and modified from Shulman (1986), Grossman (1990), Magnusson et al. (1999) and Friedrichsen et al. (2009), as shown in Fig. 8.1. This is not an empirical model but one where we use as a framework to conceptualise the approach NIE takes in enhancing the development of PCK for science teachers. At the bottom are the sources from which a science teacher's PCK is developed, adapted from Grossman (1990): (1) science learning experiences or the so-called apprenticeship of observation (Lortie 1975), (2) initial science teacher preparation, (3) classroom-teaching experiences and (4) continuing teacher professional development. The three main knowledge domains or bases which influence the development of PCK are (1) SMK, (2) GPK and (3) GCK.

At NIE, SMK development is mainly developed for the Bachelor of Arts (Education)/Bachelor of Science (Education) (BA[Ed]/BSc[Ed]) programmes through the Academic Subject (AS) modules and the Diploma programmes (DipEd) through the Subject Knowledge (SK) modules. Those taking the Postgraduate Diploma in Education (PGDE) programmes would have had already obtained their SMK preparation in a relevant academic discipline at the minimum of the undergraduate level. It had been discussed previously that SMK for the academic subject differs from SMK of school science. Hence, articulating the precise requirements for school science and supporting graduates in developing their school SMK is an important component of science education courses at the NIE.

GPK and GCK developments for all programmes are done through Education Studies (ES) courses. For GPK, the relevant ES courses deal with basic educational concepts such as pupil development, the learning and thinking process, the application of psychology in teaching and learning, and the use of instructional technologies. For GCK, the student teacher will learn about the social context within which schooling operates. These include the function of the school system in socialising citizens for economic, political and social roles in the context of a multi-ethnic and multi-cultural society such as Singapore. Student teachers will understand the rationale of major education policies and new government initiatives that impact the work of school leaders, teachers, students and other stakeholders in order to achieve the Desired Outcomes of Education laid out by MOE. At the same

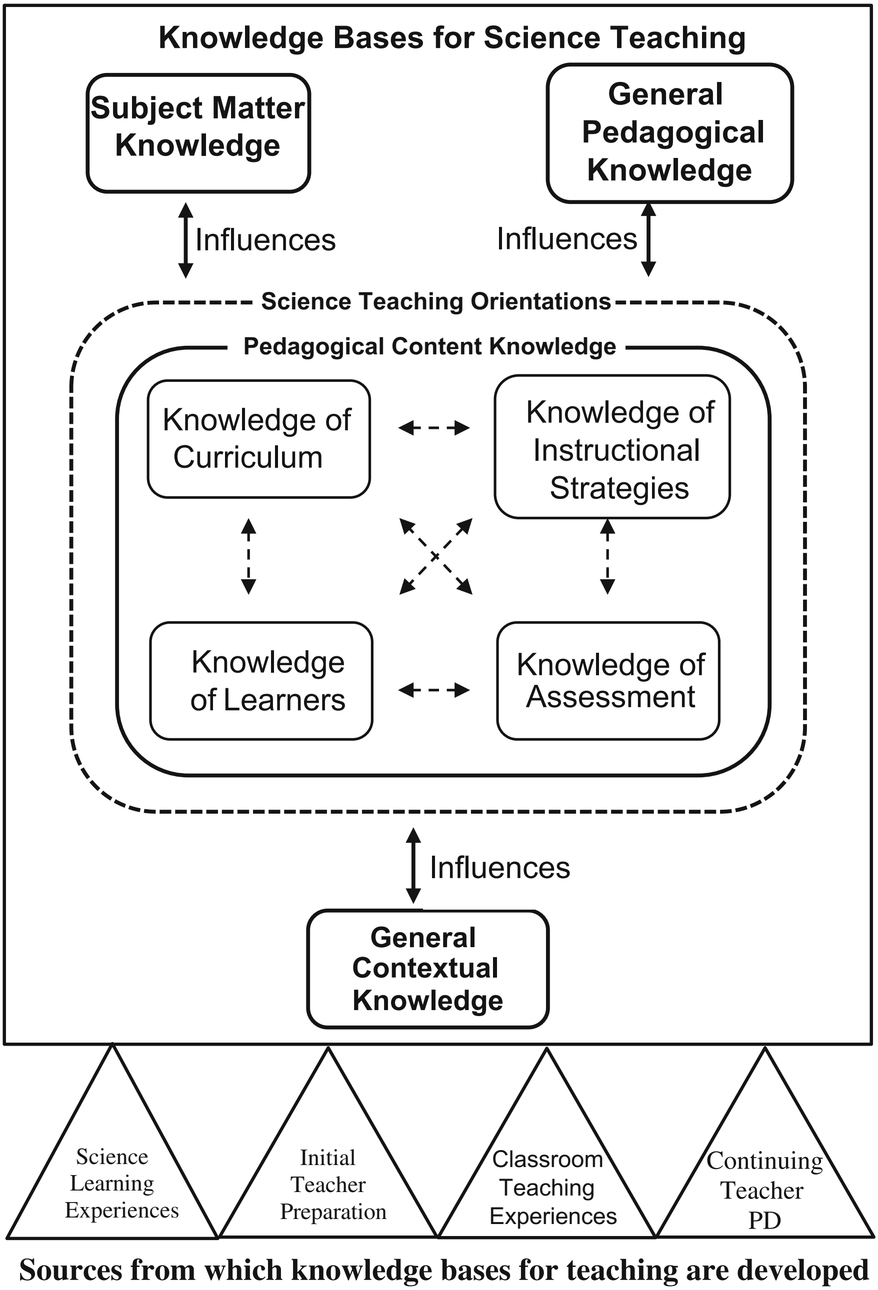

Fig. 8.1 Developing science teachers' PCK

time, they will be made aware of the diverse and multiple roles that are played by teachers in the education system.

The development of PCK, whether through transformation and/or integration, is done through the Curriculum Studies (CS) courses, which will deal with aspects such as the nature of science, the history of science, school science curriculum structure, how students learn science, student alternative conceptions, teaching and learning strategies including the use of ICT, practical work in science and assessment in science. We will elaborate by giving examples of how we have sought to develop the key components of a student teacher's science PCK: (1) knowledge of curriculum, (2) knowledge of learners, (3) knowledge of instructional strategies and (4) knowledge of assessment. While we describe snapshots of how we have sought to develop a particular PCK component in turn, it must be remembered that in reality, it would often not be possible to develop one component in isolation from the rest of the components.

8.4.1 Science-Teaching Orientations

Before delving into the PCK knowledge components, it will be needful to discuss the role that science-teaching orientations play in shaping the content and development of the PCK components. Both Grossman (1990) and Magnusson et al. (1999) included an overarching PCK component—conceptions of purposes for teaching subject matter—as the teacher's knowledge and beliefs about the goals for teaching the subject at a particular grade level and about the nature of subject as a school subject. Anderson and Smith (1987), on the other hand, described orientations as a general way of viewing teaching science and connect views with teachers' actions. This dual conceptualisation of orientations was well discussed by Friedrichsen et al. (2010) and we agree with the authors in proposing to (re)define orientations towards science teaching as consisting of a set of beliefs that teachers hold about science and science teaching, namely the goals or purposes of science teaching, the nature of science, and science teaching and learning. Rather than viewing science-teaching orientations as a PCK knowledge component, we would rather conceptualise orientations as acting as filters with which teachers develop an understanding of classroom-teaching issues and their knowledge for teaching science. For example, Hashweh (1996) found that teachers with constructivist epistemological beliefs had greater aptitude to learn from experience and to develop richer PCK. It is well-documented in the literature that while science teachers' knowledge and practice are shaped by their beliefs about science and science teaching, the relationship between orientations and practice is complex, and that teachers' orientations are not always consistent with their science-teaching practices due to contextual factors such as learner behaviours, curriculum content and assessment requirements, and influence of social expectations of stakeholders (Mansour 2009).

8.4.2 Knowledge of Curriculum

First, the knowledge of curriculum includes knowledge of the broad curriculum goals. Not least is the goal of developing students to be scientifically literate, who understand how science relates to the things around them and are able to take part in decisions as informed citizens where science and technology play a part, which is an aim of the primary and lower secondary science curriculum in Singapore. Other than understanding science as a *body of knowledge* (the products) and a *set of methods* by which this knowledge is generated (the processes), student teachers need to also be cognisant of science as a *way of knowing*. This includes the understanding that accumulated scientific knowledge is based on empirical evidence of the natural world and is verifiable, while at the same time subject to revision in the light of new evidence. In Singapore, the recently revised Lower Secondary Science curriculum has a new section known as "The Scientific Endeavour" (MOE 2012) with the aim "to deepen students' understanding of what science is and how it is practiced and applied" (p. 19). This includes the understanding of the nature of science and the interactions that science has with society, technology and the environment.

Second, the knowledge of curriculum includes understanding the big ideas in science and how key concepts are related to one another. Student teachers should understand that big ideas have far-reaching ability to explain a broad range of observable phenomena and are expressed at various points of the student's school education in ways appropriate to their stage of cognitive development. In primary science teacher preparation, there is an emphasis on understanding and integrating the big ideas of science as specified in the syllabus, which is similar to the publications from the National Academies of Science from the USA (e.g. Duschl et al. 2007). Educators in Singapore have been implementing the science curriculum using the spiral approach where concepts are revisited at greater depth, and research in the area of learning progressions in science education can further inform us on how big ideas in science can be coherently developed across years.

We have found *Content Representations* (CoRes) developed by Loughran et al. (2008) to be a useful conceptual tool for helping student teachers brainstorm and develop their initial topic-specific PCK. The CoRes template helps student teachers think about the big ideas for a particular topic and has a set of pedagogical questions that probes thinking: (1) why is it important for the students to know this? (2) Difficulties connected with teaching this idea, (3) Knowledge about student thinking which influences teaching about this idea, (4) Teaching procedures and (5) Ways of ascertaining student understanding or confusion about the idea. The CoRes template provides a scaffold for student teachers to explicitly tap on their existing understanding of the knowledge structure of the subject matter as they consider how best to teach particular topics to specific learners. As they plan and design the lesson, they will need to exercise their pedagogical judgements based on content and contextual considerations.

We want all student teachers to develop a coherent understanding of the conceptual framework of the school science curriculum and how the concepts in science can be systematically introduced to students. To this end, having student teachers involved in the content or concept analysis of the school curriculum is a useful exercise, which is undertaken during teacher preparation here. In order to teach a concept, the teacher has to explain the critical and variable attributes of the concept as well as the examples and non-examples of the concept (Herron 1996). For example, when filtration is taught, many lessons will focus on the doing of the experiment, drawing and labelling of the apparatus (filter paper, filter funnel and beaker) and the substances (mixture, filtrate and residue) involved in the process. Unfortunately, the critical attributes of the filtration process—how it actually separates substances—may be overlooked. Thus, in the pre-service chemistry pedagogy class, student teachers are advised to draw students' attention to the fact that substances bigger than the pores of the filter paper will be retained by the filter paper as the residue, while those which are smaller will pass through the filter paper as the filtrate. Animations or a demonstration with the use of a vegetable sieve and rubber balls in a beaker of water can help students visualise the sub-microscopic processes involved. Daily life examples of filtration such as making beverages using tea bags or coffee filters, or removal of dirt in a vacuum cleaner should also be presented to students to see the relevance of what they are learning to the real world. The student teachers are then asked to describe how filtration is different from decantation to illustrate a non-example of filtration. They are also advised to step back from focussing on specifics to help students see the big picture. For example, after teaching the various separation techniques such as filtration, distillation, decantation and chromatography, students should realise that the basic principle of all separation techniques is the focus on the differences between the properties of substances and the exploitation these differences to separate them. Finally, the student teachers are introduced to concept mapping (Novak 1996) to help students link all the concepts in separation techniques together, and how to assess the extent and accuracy of students' understanding through their concept maps (Markham and Mintzes 1994).

For aspiring primary science teachers, the mastery of relevant science knowledge, however, has remained a challenge because their selection for the course has been made on the basis of not having a strong graduate background in science in the first instance. Various ways have thus been used to mitigate this shortcoming; for example, familiarity with the topics in the national syllabus is maximised as a wide range of topics is randomly assigned to teachers for planning a lesson package. Tutorial activities here likewise draw across material from the biological and physical sciences equally, thereby giving wide exposure and coverage of the topics in the syllabus. Given the brevity of preparation in NIE, knowledge of subject matter of primary science teachers is ultimately dependent upon the student teacher's personal motivation to gain proficiency during this period and especially while in school. Insofar as is possible, all student teachers are made to realise that scientific inquiry should be at the heart of their instruction through modelling by lecturers during the course. Rather than a monolithic so-called scientific method, teachers are instead taught a range of inquiry pedagogies that they can flexibly apply depending on the context and purpose (Yeo and Lee 2012).

8.4.3 Knowledge of Learners

Studies have shown that pre-service teachers may have similar alternative conceptions as their students (Abell 2007); they may not realise that these conceptions are not scientifically acceptable and will not think that there is anything wrong with these conceptions when they teach them or when their students exhibit them (De Jong et al. 2002). Thus, there is a need to determine the student teachers' understanding of the concepts that they are going to teach and not assume that possession of a university degree guarantees that they have adequate understanding of the concepts (Abell 2007). Multiple choice diagnostic instruments such as those on ionic bonding (Taber 1997), ionisation energy (Tan and Taber 2009) and qualitative analysis (Tan et al. 2002) have been administered to chemistry student teachers to help them determine their understanding of the topics. The student teachers will discuss their answers in small groups and later present their groups' answers to the whole class, resolving differences in answers with their classmates. The feedback from the student teachers is that answering the questions in the diagnostic instruments and discussing the answers are valuable to them as these tasks revealed their own alternative conceptions and help clarify their understanding of the topics (Tan and Taber 2009). From this exercise, it is hoped that the student teachers will realise the importance of being able to negotiate one's understanding with one's peers and the meaningfulness of the process. With the awareness of the student alternative conceptions (as well as their own), the student teachers will be better equipped to prepare lessons to help students learn the difficult topics, negotiate and co-construct their understanding and minimise alternative conceptions.

Another important aspect of the knowledge of learners is that there are individual differences in learning and that our students come to class with different backgrounds, levels of preparation, interests, attitudes and aptitude towards learning science. Hence, addressing students' prior knowledge, knowing how to motivate different learners and the strategies to support different ability groups are important knowledge and skills for the student teacher to acquire. In short, student teachers need to learn how to pitch instruction and the tasks for particular students in a given context at the right level of challenge and support.

8.4.4 Knowledge of Instructional Strategies

We find it useful to differentiate between an instructional *model* and an instructional *strategy*. The model is the philosophical orientation with which teachers view the overall learning and teaching process, and it provides a broad plan or frame to organise instructional practices in the classroom. Models are used to select and to structure teaching strategies, technique and activities for a particular instructional emphasis. Some common instructional models used in science teaching include the learning cycle model, the cooperative learning model, the problem-based learning model and the direct-interactive teaching model. We help student teachers to make explicit links to the learning theories from behaviourist, constructivist or socio-cultural perspectives that help underpin the practice of these instructional models. In Singapore, the 5E inquiry model (Engage, Explore, Explain, Extend and Evaluate) is commonly used in primary-school science teaching to help guide teachers in the planning, implementation and assessment of a science instructional unit. More recently, we have also introduced investigative case-based learning (ICBL) as a good model (Stanley et al. 2012) to help teachers develop students' scientific literacy, while developing their twenty-first-century competencies. ICBL uses cases set in realistic contexts that allow students to carry out self-directed investigations, and incorporates three phases: problem-posing, problem-solving and peer persuasion. The existing school structure may not always allow for entirely student-centred approaches. Whole class teaching, interspersed with small group discussions and activities, or individual practice time, is not an uncommon occurrence. Hence, the direct-interactive teaching model which emphasises active learning may be a suitable model to adopt. Again, there is no best single model of learning; a teacher's approach to teaching in the classroom will be an integration of the different models to achieve a particular goal or situated to a particular situation or student groups.

Within each model, several strategies can be used to effectively achieve the learning objectives and improve student learning. Effective strategies in science instruction include questioning, use of conceptual change strategies, multi-modal representations and analogies. Often ICTs such as videos, computer simulations, data logging and video analysis are infused with the other strategies to enhance science learning. Perhaps the single most powerful tool in a teacher's repertoire is questioning. Effective teachers use their questions to elicit, clarify, probe and extend student thinking. A useful framework was derived from research in Singapore to represent productive questioning approaches such as Socratic questioning, verbal jigsaw, semantic tapestry and framing (Chin 2007). Another is Mortimer and Scott's (2003) framework for analysing discursive classroom interactions in terms of its authoritative and dialogic functions. A common conceptual change strategy is to use demonstrations together with the predict–observe–explain sequence. The demonstration is designed to elicit student alternative conceptions and designed to place student in cognitive dissonance (especially when a discrepant event is used) so that they are forced to confront and resolve any discrepancies with their earlier prediction. This elicit–confront–resolve sequence is also frequently found in the *Physics by Inquiry* guided inquiry curriculum (McDermott et al. 2000), which we have successfully used with our student teachers.

Science often involves the modelling of real-world physical phenomena using external representations that range from concrete to abstract forms: pictures, diagrams, words, graphs and equations (Gilbert 2010). Indeed, new representational tools can be developed to scaffold student learning from the more concrete physical situation to the more abstract, but generalisable forms of representation. For example, the system schema (Hinrichs 2005) can serve as a conceptual bridge between the pictorial representation and the free-body diagram, to help students better understand the application of Newton's third law in physics. This is achieved by identifying and labelling all objects of interest and the different types of interactions between objects. In chemistry, student teachers are introduced to the three main types of knowledge in chemistry, experiences, models and visualisations (Talanquer 2011) and the importance of teaching all three types of knowledge to students. Experiences are encounters with chemical substances and phenomena using our senses, usually sight, smell and hearing, and through the use of instruments such as pH metres and spectrophotometers. Models are used to describe, explain and predict the chemical behaviour and interaction of substances, while visualisations are "static and dynamic visual signs (from symbols to icons) developed to facilitate qualitative and quantitative thinking and communication about both experiences and models in chemistry" (Talanquer 2011, p. 187). Thus, to understand a phenomenon such as the reaction of magnesium with dilute hydrochloric acid, students need to see the phenomenon of a magnesium strip moving about in a beaker of dilute hydrochloric acid with bubbles forming around the metal. Heat is also given off and the metal becomes smaller and smaller until it disappears and the bubbling also stops. Teachers need to explain that there is a reaction between the hydrogen ions (or hydroxonium ion, depending on the level of the students) and the magnesium metal in which the magnesium atoms lose electrons to the hydrogen ions, forming magnesium ions which go into solution and hydrogen gas which escapes as bubbles into the atmosphere. In order to visualise the explanation, animations can be shown to the students and chemical equations can be used to summarise the reaction between the metal and the acid or the redox reaction between the metal atom and the hydrogen ions. If the focus of the phenomenon is on the rate of the metal-acid reaction, graphs can also be used to illustrate the progress of the reaction and how concentration of the acid, size of the metal and temperature can impact on the rate of reactions. In summary, learning chemistry requires more than being able to "remember the facts": the students have to be able to relate the experiences, models and visualisations involved to derive meaning in their learning, and the teacher has to plan lessons which allow students to accomplish this.

One aspect of primary science teaching in NIE deserves mention with regard to developing deep knowledge of inquiry science: its use of Knowledge Building pedagogies and software (Yeo and Lee 2010, 2012). In some courses, pre-service primary teachers are made to partner with nearby primary schools to facilitate inquiry science lessons over a number of weeks in a term. Working in small groups around a common theme such as seed germination, they facilitate student questions and simple science investigations that originate from the students themselves. Even with young children, they have never failed to amaze our teachers with their diverse projects such as whether beans that are larger will germinate faster than smaller ones or whether crowding conditions affect the rate of seed growth. Because of the emphasis on working on ideas (i.e. theories) that can be improved in Knowledge Building, student initiative is not hampered and their trajectory of learning is potentially unlimited. Part of the assessment for the course involves videotaping the facilitation of teaching and giving critical peer commentary based on both teaching theory and Knowledge Building principles. While student teachers have said that this pedagogy was initially unfamiliar and extremely demanding in all senses of the word, the overall assessment was that it was an invaluable learning experience to be working at the forefront of student-led inquiry, a far-cry from cookbook style activities so common in their experience. Moreover, organising links with schools in the community to support better teacher–pupil ratios during inquiry projects has been a good example of the synergy derived between schools and pre-service teachers as part of practice-based teaching.

8.4.5 Knowledge of Assessment

Assessment is essentially finding out what students know and are able to do in relation to the learning outcomes of instruction. A key aspect of the knowledge of assessment is the ability to construct and implement assessment, using a range of strategies, at the right time and for the right purpose. Knowing how to reliably evaluate student learning has been an important part of assessment and this includes knowing the strategies to elicit prior ideas, to monitor student progress and to guide instruction. Seen in the context of a 2009 report by the Primary Education Review and Implementation Committee (MOE 2009) that endorsed more holistic forms of assessment, much effort has been taken to help primary science student teachers develop and use rubrics coupled with feedback that assess a range of competencies in the subject. Teaching forms of school-based assessment that departs from paper-and-pencil formats have also been given priority during the course. Active assessment strategies (Naylor and Keogh 2007) such as annotated drawings, card sorts, KWL grids, deliberate mistakes, graphic organisers and concept cartoons have been introduced to student teachers. Other examples of alternative modes of assessment in science include concept mapping, debates, journals, learning trails, portfolios and performance tasks, such as designing a container to keep ice cream from melting or building a solar cooker to cook an egg.

8.4.6 Developing PCK in Real Classroom Contexts

At NIE, we try to acculturate our student teachers early into the actual school environment so as to help them build their contextual knowledge base on the realities and issues related to teaching in schools. For example, for our 4-year BA (Ed)/BSc(Ed) programmes, the school-based practicum for student teachers is spread throughout the programme and is developmental in nature. It comprises four school attachment periods, one in each year: a 2-week School Experience, a 5-week Teaching Assistantship, a 5-week Teaching Practice and a final 10-week Teaching Practice. For the first 2 years, student teachers observe classroom teaching and do assisted teaching. They start teaching independently only in the last two years. The PGDE programmes, on the other hand, have a 4-week Enhanced School Experience (ESE) programme before they begin their 1-year full-time formal lessons at NIE. This is to induct student teachers into classroom teaching and to help them gain contextual knowledge of the school environment such as the school organisational structure and protocol, and expectations of key stakeholders such as parents, students and the school leadership team. They also keep a journal and write their observations and reflections related to the broad aspects of science teaching and learning; for example, the goals and structure of the curriculum, teaching approaches, difficulties students having with learning science, practical work and assessment. Similar to the undergraduates, they also have a 10-week practicum where they have to put all the education theories that they have learnt into practice.

While student teachers can develop their initial topic-specific PCK through lesson planning and microteaching, the limitation is the absence of a real classroom setting with which student teachers actively make decisions as they respond to the problematic nature of the teaching and learning experiences with real students. Hence, providing student teachers with real teaching practice plays a major role in helping them to bridge the theory and practice gap and to develop their personal teaching competence. We have in recent years introduced a component of practice-based work (PbW) in some of our high school PGDE Physics courses to allow student teachers to experience the interactional and dynamic nature of teaching early in the programme before their final 10-week teaching practice. The student teachers are assigned specific topics to prepare and to review the literature regarding student alternative conceptions and difficulties associated with learning the concepts in the topic. They also research on a specific learning issue or instructional strategy pertaining to instruction in science such as constructivist and sociocultural perspectives to learning in science, the use of multi-modal representations and productive classroom discourse. The student teachers are assigned into groups where they team teach a specific topic three times to three different groups of students. Each group of student teachers collaboratively prepares a teaching package with inputs from peers, NIE instructors and teacher-mentors from partnering schools. The lessons are video-recorded to help with the post-lesson reflection. Through PbW, the student teachers are given the opportunity to develop their PCK and gain a better understanding of the theory–practice nexus through iterative cycles of research on learning issues, lesson planning, implementation and evaluation.

PGDE Chemistry student teachers also have school-based sessions included in their high school chemistry pedagogy course. To prepare the student teachers for the school-based sessions, the student teachers have to answer the questions in a diagnostic quiz on ionisation energy and read up a relevant paper (Tan and Taber 2009) to determine their understanding of the topic as well as to introduce them to chemistry education research papers. As mentioned in an earlier section, many of the student teachers will have similar alternative conceptions as the students and this exercise will help them address their alternative conceptions as well as realise the usefulness of the research papers as a source of information on students' learning difficulties in various chemistry topics and a repository of suggestions on how to address these difficulties. The next task given to the student teachers is to search and read up on student difficulties in the topics which are chosen by the school and prepare multiple choice questions based on these learning difficulties and possible student alternative conceptions. In addition, they need to think of ways to address the learning difficulties and alternative conceptions. At the school, for three to four sessions, they will administer different sets of questions to the students who come for these sessions, review the students' answers with them and address difficulties that the students have. Towards the end of a session, the student teachers will administer a few more questions to check whether the students have acquired more acceptable scientific conceptions. The school-based sessions provide the context for later lessons on pedagogy and assessment as well as the impact on research on practice.

8.5 Conclusion

This chapter has focussed on the elaborate knowledge base that science teachers require in order to be effective in their profession, with particular emphasis on developing their PCK as a vital part of their learning and growth as a teacher. Currently, the broad goal of school science seems to be shifting towards developing students' scientific literacy with greater focus given to viewing science as being dynamic, and set in a social and cultural context. This includes the ability to understand media accounts of science, to recognise and appreciate the contributions of science in society, and to be able to use science in decision-making on both everyday and socio-scientific issues. As Singapore advances towards the threshold of yet another phase of education—one that is student centric and values driven, there is a need to develop teachers who are competent and confident to assume their roles in helping our new generation of learners thrive in this new landscape.

The student teacher's time during the initial teacher preparation phase is indeed just the start of a long journey. It will not be possible for teachers to acquire all the necessary knowledge and skills to be effective teachers in such a short time. What we can try to inculcate are positive values such as the love for (re-)learning on the job, passion for science, modelling the qualities of good teaching and putting a human face to science. Teacher education will not be content delivery per se (else we could as well learn everything online) but we in NIE foreground learning with and alongside a human teacher who loves the subject matter and one guides youth along in the best way, given their needs, interests and aspirations. PCK and indeed all science teaching and education in general have to be governed by such an ethic of care for the whole person (Noddings 2013). Educating teachers as persons with all their fallibilities is arguably our aim, not just the preparation of instructors in science. Indeed, the teacher education in the twenty-first century does not negate what the essence of teaching was in the past, it might look different but at its heart we believe that it is still the same.

References

Abell, S. K. (2007). Research on science teacher knowledge. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 1105–1149). Mahwah, NJ: Lawrence Erlbaum Associates, Publishers.

Abell, S. K. (2008). Twenty years later: Does pedagogical content knowledge remain a useful idea? *International Journal of Science Education, 30*(10), 1405–1416.

Anderson, C. W., Smith, E. L., & Richardson-Koehler, V. (1987). Educator's Handbook: A Research Perspective. *Educator's handbook: a research perspective*.

Appleton, K. (2008). Developing science pedagogical content knowledge through mentoring elementary teachers. *Journal of Science Teacher Education, 19*(6), 523–545.

Black, P., Harrison, C., & Lee, C. (2003). *Assessment for learning: Putting it into practice*. McGraw-Hill Education (UK).

Boon, G. C., & Gopinathan, S. (2006). The development of education in Singapore since 1965. In S. K. Lee, C. B. Goh, B. Fredriksen, & J. P. Tan (Eds.), *Toward a better future: Education and training for economic development in Singapore since 1965* (pp. 12–38). The World Bank and the National Institute of Education at Nanyang Technological University.

Chin, C. (2007). Teacher questioning in science classrooms: Approaches that stimulate productive thinking. *Journal of Research in Science Teaching, 44*(6), 815–843.

Clarke, D., & Hollingsworth, H. (2002). Elaborating a model of teacher professional growth. *Teaching and Teacher Education, 18*(8), 947–967.

Cochran, K. F. (1993). Pedagogical content knowing: An integrative model for teacher preparation. *Journal of Teacher Education, 44*(4), 263–272.

Corrigan, D., Dillon, J., & Gunstone, R. (Eds.). (2011). The professional knowledge base of science teaching. Springer Science+Business Media.

Darling-Hammond, L., et al. (2005). *Preparing teachers for a changing world: What teachers should learn and be able to do*. San Francisco, CA: Jossey Bass.

De Jong, O. (2009). Exploring and changing teachers' pedagogical content knowledge: An overview. In O. De Jong & L. Halim (Eds.), *Teachers' professional knowledge in science and mathematics education: Views from Malaysia and abroad*. Malaysia: Universiti Kebangsaan Malaysia.

De Jong, O., Veal, W. R., & Van Driel, J. H. (2002). Exploring chemistry teachers' knowledge base. In O. D. J. J. K. Gilbert, R. Justi, D. F. Treagust, & J. H. Van Driel (Eds.), *Chemistry education: Towards research-based practice* (pp. 369–390). Dordrecht: Kluwer Academic Publishers.

Deng, Z. (2007). Knowing the subject matter of a secondary-school science subject. *Journal of Curriculum Studies, 39*(5), 503–535.

Duschl, R. A., Schweingruber, H. A., & Shouse, A. W. (2007). *Taking science to school: Learning and teaching science in grades K-8*. Washington, DC: The National Academies Press.

Fischer, H. E., Borowski, A., & Tepner, O. (2012). Professional knowledge of science teachers. In *Second international handbook of science education* (pp. 435–448). The Netherlands: Springer.

Friedrichsen, P., Van Driel, J. H., & Abell, S. K. (2010). Taking a closer look at science teaching orientations. *Science Education, 95*(2), 358–376.

Friedrichsen, P. J., Abell, S. K., Pareja, E. M., Brown, P. L., Lankford, D. M., & Volkmann, M. J. (2009). Does teaching experience matter? Examining biology teachers' prior knowledge for teaching in an alternative certification program. *Journal of Research in Science Teaching, 46* (4), 357–383.

Gess-Newsome, J., & Lederman, N. G. (1993). Preservice biology teachers' knowledge structures as a function of professional teacher education: A year-long assessment. *Science Education, 77* (1), 25–45.

Gess-Newsome, J., & Lederman, N. G. (Eds.). (1999). *Examining pedagogical content knowledge*. *Science technology education library* (Vol. 6, p. 303). Kluwer Academic Publishers.

Gilbert, J. (2010). The role of visual representations in the learning and teaching of science: An introduction. *Asia-Pacific Forum on Science Learning and Teaching, 11,* 1–19.

Grossman, P. L. (1990). *The making of a teacher: Teacher knowledge and teacher education*. New York: Teachers College Press.

Hashweh, M. Z. (1996). Effects of science teachers' epistemological beliefs in teaching. *Journal of Research in Science Teaching, 33*(1), 47–63.

Herron, J. D. (1996). *The chemistry classroom: Formulas for successful teaching*. Washington, DC: American Chemical Society.

Kind, V. (2009). Pedagogical content knowledge in science education: Potential and perspectives for progress. *Studies in Science Education, 45*(2), 169–204.

Loughran, J. (2013). Pedagogy: Making sense of the complex relationship between teaching and learning. *Curriculum Inquiry, 43*(1), 118–141.

Loughran, J., Mulhall, P., & Berry, A. (2008). Exploring pedagogical content knowledge in science teacher education. In D. Psillos, P. Kariotoglou, V. Tselfes, G. Bisdikian, G. Fassoulopoulos, E. Hatzikraniotis, & M. Kallery (Eds.), *International Journal of Science Education, 30*(10), 1301–1320.

Lortie, D. C. (1975). *Schoolteacher: A sociological study*. Chicago: University of Chicago Press.

Low, E. L., Taylor, P. G., Joseph, J., & Atienza, J. C. (Eds.). (2009). *A teacher education model for the 21st century*. Singapore: National Institute of Education, Nanyang Technological University. Retrieved from the NIE website: https://www.nie.edu.sg/docs/default-source/te21_docs/te21-online-version—updated.pdf?sfvrsn=2

Luft, J. A., Roehrig, G. H., & Patterson, N. C. (2003). Contrasting landscapes: A comparison of the impact of different induction programs on beginning secondary science teachers' practices, beliefs, and experiences. *Journal of Research in Science Teaching, 40*(1), 77–97.

Magnusson, S., Krajcik, J., & Borko, H. (1999). Nature, sources, and development of pedagogical content knowledge for science teaching. In J. Gess-Newsome & N. Lederman (Eds.), *PCK and science education* (Vol. 6, pp. 95–132). Kluwer Academic Publishers.

Mansour, N. (2009). Science teachers' beliefs and practices: Issues, implications and research agenda. *International Journal of Environmental & Science Education, 4*(1), 25–48.

Markham, K. M., & Mintzes, J. J. (1994). The concept map as a research and evaluation tool: Further evidence of validity. *Journal of Research in Science Teaching, 31*(1), 91–101.

McDermott, L. C., Shaffer, P. S., & Constantinou, C. P. (2000). Preparing teachers to teach physics and physical science by inquiry. *Physics Education, 35*(6), 411–416.

Ministry of Education. (2008). *More support for school's "Teach less, learn more" initiatives* [Press release]. Singapore: Ministry of Education.

Ministry of Education. (2009). *Report of the primary education review and implementation committee*. Retrieved from http://www.moe.gov.sg/media/press/files/2009/04/peri-report.pdf

Ministry of Education. (2012). *Science syllabus: Lower secondary express/normal (academic)*. Retrieved from https://www.moe.gov.sg/docs/default-source/document/education/syllabuses/sciences/files/science-lower-secondary-2013.pdf

Morris, A. K., & Hiebert, J. (2011). Creating shared instructional products: An alternative approach to improving teaching. *Educational Researcher, 40,* 5–14.

Mortimer, E. F., & Scott, P. H. (2003). *Meaning making in science classrooms*. Milton Keynes: Open University Press.

Low, E. L., Taylor, P. G., Joseph, J., & Atienza, J. C. (Eds.). (2009). *A teacher education model for the 21st century*. Singapore: National Institute of Education, Nanyang Technological

University. Retrieved from the NIE website: https://www.nie.edu.sg/docs/default-source/te21_docs/te21-online-version—updated.pdf?sfvrsn=2

Naylor, S., & Keogh, B. (2007). Active assessment: Thinking, learning and assessment in science. *School Science Review, 88*(325), 73–79.

Noddings, N. (2013). *Education and democracy in the 21st century*. New York: Teachers College Press.

Novak, J. D. (1996). Concept mapping: A tool for improving science teaching and learning. In D. F. Treagust, R. Duit, & B. J. Fraser (Eds.), *Improving teaching and learning in science and mathematics* (pp. 32–43). New York: Teachers College Press.

Park, S., & Oliver, J. S. (2008). Revisiting the conceptualisation of pedagogical content knowledge (PCK): PCK as a conceptual tool to understand teachers as professionals. *Research in Science Education, 38*(3), 261–284.

Pea, R. D., & Collins, A. (2008). Learning how to do science education: Four waves of reform. In Y. Kali, M. C. Linn, & J. E. Roseman (Eds.), *Designing coherent science education*. New York: Teachers College Press.

Schön, D. (1983). *The reflective practitioner: How practitioners think in action*. London: Temple Smith.

Schwab, J. J. (1969). The practical: A language for curriculum. *The School Review, 78*(1), 1–23.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*(2), 4–14.

Shulman, L. S. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review, 57*(1), 1–22.

Stanley, E. D., Waterman, M. A., Wong, D., & Tan, H. K. (2012). Developing 21st century skills with investigative cases: Building global awareness and informing choices about energy. *Biology International, 50,* 95–108.

Taber, K. S. (1997). Student understanding of ionic bonding: Molecular versus electrostatic framework? *School Science Review, 78*(285), 85–95.

Talanquer, V. (2011). Macro, submicro, and symbolic: The many faces of the chemistry “triplet”. *International Journal of Science Education, 33*(2), 179–195.

Tamir, P. (1988). Subject matter and related pedagogical knowledge in teacher education. *Teaching and Teacher Education, 4*(2), 99–110.

Tan, K. C. D., Goh, N. K., Chia, L. S., & Treagust, D. F. (2002). Development and application of a two-tier multiple choice diagnostic instrument to assess high school students’ understanding of inorganic chemistry qualitative analysis. *Journal of Research in Science Teaching, 39*(4), 283–301.

Tan, K. C. D., & Taber, K. S. (2009). Ionization energy: Implications of pre-service teachers’ conceptions. *Journal of Chemical Education, 86*(5), 623–629.

Veal, W. R., & MaKinster, J. G. (1999). Pedagogical content knowledge taxonomies. In P. Penelope, B. Eva, & M. Barry (Eds.), *Electronic Journal of Science Education, 3*(4), 656–661.

Verloop, N., Van Driel, J., & Meijer, P. (2001). Teacher knowledge and the knowledge base of teaching. *International Journal of Educational Research, 35*(5), 441–461.

Yeo, J., & Lee, Y.-J. (2010). Situating science inquiry in a knowledge creation metaphor of learning. In Y.-J. Lee (Ed.), *The world of science education: Handbook of research in Asia* (pp. 335–354). Rotterdam: Sense Publishers.

Yeo, J., & Lee, Y.-J. (2012). Knowledge advancement in environmental science through knowledge building. In D. K. C. Tan & M. Kim (Eds.), *Issues and challenges in science education research: Moving forward* (pp. 317–322). Dordrecht: Springer.