International Journal of Science Education

ISSN: 0950-0693 (Print) 1464-5289 (Online) Journal homepage: http://www.tandfonline.com/loi/tsed20

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To cite this article: Hui Jin, Xin Wei, Peiran Duan, Yuying Guo & Wenxia Wang (2016) Promoting cognitive and social aspects of inquiry through classroom discourse, International Journal of Science Education, 38:2, 319-343, DOI: 10.1080/09500693.2016.1154998

To link to this article: http://dx.doi.org/10.1080/09500693.2016.1154998

Published online: 02 Mar 2016.

INTERNATIONAL JOURNAL OF SCIENCE EDUCATION, 2016
VOL. 38, NO. 2, 319–343
http://dx.doi.org/10.1080/09500693.2016.1154998

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Promoting cognitive and social aspects of inquiry through classroom discourse

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ABSTRACT

We investigated how Chinese physics teachers structured classroom discourse to support the cognitive and social aspects of inquiry-based science learning. Regarding the cognitive aspect, we examined to what extent the cognitive processes underlying the scientific skills and the disciplinary reasoning behind the content knowledge were taught. Regarding the social aspect, we examined how classroom discourse supported student learning in terms of students' opportunities to talk and interaction patterns. Our participants were 17 physics teachers who were actively engaged in teacher education programs in universities and professional development programs in local school districts. We analyzed one lesson video from each participating teacher. The results suggest both promises and challenges. Regarding the cognitive aspect of inquiry, the teachers in general recognized the importance of teaching the cognitive processes and disciplinary reasoning. However, they were less likely to address common intuitive ideas about science concepts and principles. Regarding the social aspect of inquiry, the teachers frequently interacted with students in class. However, it appeared that facilitating conversations among students and prompting students to talk about their own ideas are challenging. We discuss the implications of these findings for teacher education programs and professional development programs in China.

ARTICLE HISTORY
Received 20 October 2015
Accepted 12 February 2016

KEYWORDS
Inquiry; classroom discourse; cognitive processes; disciplinary reasoning

Introduction

Since the publication of Joseph Schwab's (1958) seminal article on inquiry in science education, the goal of science learning has shifted from learning the end products of science to learning the process of 'doing' science. As a means of doing science, inquiry is emphasized as an important learning goal in science curriculum in many countries (Abd-El-Khalick et al., 2004). In the U.S.A, *The National Science Education Standards* provides the following definition of inquiry (National Research Council [NRC], 1996), which is widely used in policy documents and research articles:

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> Scientific inquiry refers to the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. Scientific inquiry also refers to the activities through which students develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world. (p. 23)

Since the term 'inquiry' has been interpreted in many different ways, the newly released NRC framework for K-12 science education (NRC, 2012) articulates eight scientific practices to better specify what is meant by inquiry in science. The framework highlights the following point: 'Students will themselves engage in the practices and not merely learn about them secondhand. Students cannot comprehend scientific practices, nor fully appreciate the nature of scientific knowledge itself, without directly experiencing those practices for themselves' (p. 30).

In China, K-12 education is primarily driven by tests. The national college entrance exam and various middle and high school entrance exams at the provincial level have led to rote learning and stifling critical thinking. They have also placed tremendous pressure on teachers, forcing them to rely on using lectures to 'efficiently' transmit a large quantity of content to their students (Zhao & Qiu, 2010). One may argue that test-driven education has enabled Chinese students to become top performers in international assessments such as Programme for International Student Assessment (PISA) (Organisation for Economic Co-operation and Development, 2013). However, test scores do not necessarily reflect the capability of doing science. A recent large-scale survey shows that only about 3% of Chinese adults have achieved basic scientific literacy, in comparison to 28% of American adults (Ren, 2011). Although Mainland China has produced many top test performers, it may not have prepared students to become creative, critical, and independent thinkers. Recognizing the limitations of exam-oriented systems and the need to promote inquiry-based teaching, China embarked on a science curriculum reform in 1999 (Guan & Meng, 2007). Curriculum standards for all science subjects were redesigned to set *inquiry and science literacy* as a central focus. In response to this paradigm shift, many local schools encourage science teachers to design and teach inquiry lessons, and professional development opportunities are provided to help teachers learn about inquiry-based instruction. However, little research to date has investigated how Chinese teachers designed and taught inquiry-based lessons or has evaluated the quality of teachers' self-designed inquiry lessons.

The present study will contribute to this line of research. We consider two views in setting our research goal. First, Keys and Bryan (2001) argue that 'teachers are intelligent decision makers who will have their own perspectives on and definitions of inquiry' (p. 632). They further call for more research on inquiry-based instruction that has been designed by teachers rather than researchers. Second, classroom discourse plays a pivotal role in supporting students' inquiry-based learning (Clark, Weinberger, Jucks, Spitulnik, & Sallace, 2003; Lemke, 1990; Rosebery, Warren, & Conant, 1992). Well-designed activities may not result in expected learning outcomes because of ineffective classroom discourse. In bringing these two perspectives together, we aim at examining how classroom discourse supports science learning in physics teachers' self-designed inquiry lessons. Moreover, our participants were expert teachers who were actively involved in teacher preparation programs in universities and senior teachers[1] who were actively involved in district professional development programs. Currently, expert teachers and senior teachers are the main actors who drive the reform at the school level. Studying their teaching practices will provide important implications for science teacher education and professional development in China.

In this study, we heavily drew upon the science education policy documents in the U.S.A , because they were the major references used to develop the national science curriculum standards in China. The NRC framework (2012) specifies inquiry as eight scientific practices to highlight 'the range of cognitive, social, and physical practices that it [inquiry] requires' (p. 30). Empirical studies suggest that U.S. school science tends to emphasize the physical aspect of inquiry (e.g. Inquiry is doing hands-on activities), while largely dismissing the cognitive and social aspects. This point was provided in a book on inquiry in the U.S. science classrooms: *The Impact of State and National Standards on K-12 Science Teaching* (Sunal & Wright, 2005). Although no large-scale studies have been conducted in China, similar patterns could exist due to the lack of resources and professional development programs on inquiry-based teaching in China. To emphasize the cognitive and social aspects of inquiry, we define scientific inquiry as specialized ways of doing, knowing, thinking, and talking that scientists employ when conducting research and communicating information in the science community. Our research question is: How do Chinese physics teachers use classroom discourse to promote the cognitive and social aspects of inquiry-based learning?

Research context: curriculum reform in China

In 1999, the Ministry of Education initiated China's New National Curriculum Reform to establish a new curriculum system to meet the requirement of the twenty-first century (Guan & Meng, 2007). Within the scope of the national reform, science curricula underwent significant transformation. Due to the focus of this study, we specifically address the systemic transformations of the high school physics curriculum, although similar changes took place in other science subjects and school levels as well.

The reform of the high school physics curriculum took place at three levels. At the national level, a committee was established to design curriculum standards, with inquiry and science literacy as the central focus. The committee was composed of professors in science education and natural science, and experienced teachers selected from across the country. The committee used *Science for All Americans* and *Benchmarks for Science Literacy* as a major reference source. It released *Physics Curriculum Standards* (PCS) in 2003 (Ministry of Education of the People's Republic of China, 2003). The PCS was developed with an aim at promoting the development of (1) scientific knowledge and skills, (2) science processes and methods (i.e. science inquiry), and (3) scientific attitudes and values. It encourages teachers to incorporate all three components in classroom teaching, while specifically emphasizing the integration of science inquiry and scientific knowledge and skills. In PCS, science inquiry is specified as seven stages of doing science: proposing research questions, making hypotheses, designing experiments, conducting experiments and collecting data, analyzing data and using evidence to justify conclusions, evaluating results and processes of experiments, and reporting and communicating results of experiments. Physics content knowledge is elaborated in terms of 12 modules, including 2 required modules and 10 selective modules. To meet graduation requirement, each student must complete the two required modules and at least one selective module. Each module contains two to four units and takes one semester to complete. Teachers are strongly encouraged to integrate the seven stages of doing science with the content modules.

At the provincial level,[2] local education departments formed a committee to select textbooks and associated materials, and develop provincial assessments. The committee consists of teacher coaches, administrators, and sometimes parent representatives. Teacher coaches were expert teachers who were hired by the education department to work on professional development programs for in-service teachers. Local schools recommended parent representatives who were actively involved in school activities during the past. The inclusion of parent representatives is very important, as family commitment to education is deeply embedded in Chinese culture. Administrators such as school principals were also included; they brought knowledge of educational policy and instructional resources. The committee selected two or more textbooks and associated materials (e.g. teachers' guide and student practice books) for teachers to use. To ensure the alignment between curriculum and assessments, the expert teachers are also responsible for developing grade level assessments and high school graduation assessments.

At the school level, science teachers used the selected textbooks and teaching materials to teach. Teachers teaching the same science topic often plan lessons together. In China, teachers routinely participate in Teaching and Research meetings to share ideas and resources on teaching. Many schools use Teaching and Research meetings as professional development opportunities for teachers to learn about inquiry-based teaching. During the meetings, teachers often discuss the curriculum standards and its impact on classroom teaching, watch and discuss exemplar inquiry-based lessons, and share ideas about designing and teaching inquiry lessons. Some schools also invite university professors to give talks about inquiry-based teaching.

Conceptual framework

In this study, we investigated how Chinese physics teachers used classroom discourse to promote the cognitive and social aspects of inquiry. We reviewed relevant literature to develop the conceptual framework (Figure 1). Regarding the cognitive aspect of inquiry, we reviewed the literature on inquiry-based learning and found that a crucial question is: What should be taught in science classrooms? Based on this body of literature, we identified two competencies that are important for science learning in schools. Regarding the social aspect of inquiry, we reviewed the literature of classroom discourse, and found that a highlighted question is: How should science be taught in science classrooms?

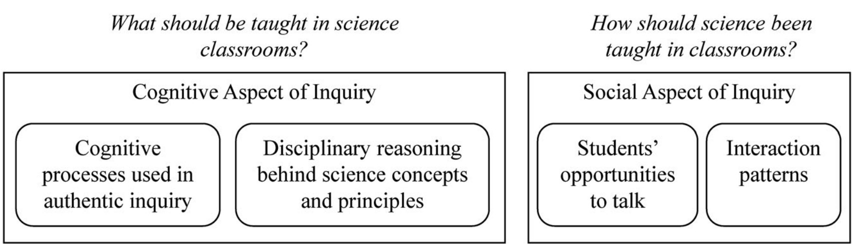

Figure 1. Conceptual framework.

Based on this stream of literature, we identified two dimensions of classroom discourse that indicate how science should be taught.

Cognitive aspect of inquiry: what should be taught in science classrooms?

We examined the changing perspectives on inquiry in the history of science education. This historical examination allowed us to identify two important competencies of inquiry that should be taught in science classrooms. Our literature review suggests that the perspective of inquiry shifted across three stages: science process skills in the National Science Foundation (NSF) curriculum reform movement, science inquiry in the national standards movement, and scientific practices in current Next Generation Science Standards (NGSS).

During the curriculum reform era, inquiry was conceptualized as individual process skills that reflect the behaviors of scientists; these process skills usually include observing, classifying, inferring, controlling variables, and so on (Sanderson & Kratochvil, 1971). This perspective of inquiry had a significant influence on school science education until the early 1990s. In science classrooms, process skills were often taught in a fragmented manner and without connection to science content (Abd-El-Khalick et al., 2004; Barrow, 2006; Gabel, 2006). Such instructions have been highly criticized because they focus on procedural skills and do not promote scientific thinking (Bybee, 1997). Moreover, the assumption that students can learn inquiry skills separately from science content significantly contributed to the lack of success of inquiry-based teaching in the 1980s and early 1990s (Roth & Roychoudhury, 1993). The perspective reflected in the science process skills is in marked contrast to the view of inquiry stressed in the NRC framework. According to the NRC framework, 'engaging in scientific inquiry requires coordination of both knowledge and skill simultaneously' (2012, p. 41).

In 1996, the *National Science Education Standards* (NSES) (NRC, 1996) was released. The NSES and *Inquiry and the National Science Education Standards* (NRC, 2000) emphasize five essential features of inquiry: scientifically oriented questions that will engage the students; evidence collected by students that allows them to develop and evaluate their explanations to the scientifically oriented questions; explanations developed by students from their evidence to address the scientifically oriented questions; evaluation of their explanations, which can include alternative explanations that reflect scientific understanding; and communication and justification of their proposed explanations. They reflect the ways of thinking that scientists use when exploring the material world. However, teachers may teach the standards in ways that are not as expected. Empirical studies showed that teachers often asked students to follow procedures of conducting scientific experiments rather than engaging them in active thinking (Lunetta, Hofstein, & Clough, 2007; van Rens, Pilot, & van der Schee, 2010). Teachers also tended to equate hands-on activities with inquiry-based teaching, and therefore engaged students in activities that were hands-on but not minds-on (Banilower, Smith, Weiss, & Pasley, 2006).

To clarify the meaning of inquiry, the newly released NRC framework and NGSS specify inquiry as eight scientific practices; the eight scientific practices are asking questions; developing and using models; planning and carrying out investigations; analyzing and interpreting data; using mathematics and computational thinking; constructing explanations; engaging in argument from evidence; and obtaining, evaluating, and communicating information (NGSS Lead States, 2013; NRC, 2012). Along the same line, many researchers have pointed out that the goal of inquiry-based teaching is to teach *authentic* scientific inquiry—the specialized ways of thinking, both discipline-general and discipline-specific, that scientists employ while raising research questions, making predictions, analyzing data, constructing scientific models and explanations, and so on (Driver, Asoko, Leach, Mortimer, & Scott, 1994; Roth et al., 2006).

The shift of perspectives across these three stages suggests two important goals of inquiry-based science teaching: to teach the ways of thinking that scientists perform when doing science, and to teach the specialized ways of reasoning behind scientific knowledge. In line with these two teaching goals, we identified two important competencies that should be developed in science classrooms: cognitive processes and disciplinary reasoning.

Cognitive processes

One important lesson learned in the history of science education is that the thinking behind the behaviors of scientists should be at the center of scientific inquiry. Chinn and Malhotra (2002) compared the scientific experiments conducted by scientists with 'textbook inquiry activities' and found that inquiry tasks commonly used in schools evoked reasoning processes that were qualitatively different from the processes employed in authentic scientific inquiry. For example, in real science, scientists aim at developing and refining theoretical models in response to empirical evidence, while in school science, students are often expected to uncover surface-level patterns (e.g. plants grow faster in the light than in the dark; plants have stems and leaves). Chinn and Malhotra define the reasoning processes required to do authentic inquiry as 'cognitive processes'. This definition emphasizes that the thinking underlying the inquiry activities or behaviors is essential. Therefore, we identify cognitive processes as one essential competency to be developed in science classrooms. Based on the ideas from Chinn and Malhotra and the Chinese National Curriculum Standards for physics, we propose that the cognitive processes of seven scientific skills should be developed in inquiry-based lessons in the context of Chinese science education. The seven skills fall into three groups: generating questions, designing studies, and explaining results. The scientific skills and the cognitive processes underlying these skills are presented in Table 1.

Disciplinary reasoning

A second lesson science education researchers learned in the history of science education is that conceptual understanding of core scientific concepts and principles should be an indispensable part of inquiry. In science, some concepts and principles are particularly difficult for students, because the specialized ways of reasoning underlining those concepts and principles are complex and counterintuitive (Chi, 2005; Jin & Anderson, 2012; Jin & Wei, 2014). Although students' intuitive ideas vary from topic to topic, the informal ways of reasoning behind those ideas share common characteristics. When explaining phenomena, students often rely on *linear and sequential* reasoning to understand their experiences with the material world (Chi, 2005; Grotzer & Bell, 1999). This way of reasoning often assumes linear connections between observations and theories/models. For example, students all have the experience that in order to move an object, a force must be exerted on that object. Based on this experience, they construct a common intuitive

Table 1. The scientific skills and cognitive processes.

Categories	Teaching Scientific Skills Only	Teaching Cognitive Processes behind Scientific Skills
Generating questions: generating research questions	Students propose questions for investigations. The teacher may provide an evaluation (e.g. It is a good question.). However, there is no discussion regarding how to evaluate a research question	Students propose questions for investigation. The class discussion involves a rationale that explains why a research question is a good one. For example, good research questions are investigable. Such questions are usually about comparison, cause and effect, prediction, design and make, exploratory, descriptive, pattern-seeking, problem-solving, and validation of a model (Chin & Kayalvizhi, 2002)
Designing studies: (1) controlling variables, (2) planning procedures, and (3) making predictions	Students follow predetermined procedures. The class discussion focuses on what to do, but not why the investigation should be carried out in that way	Students discuss the conceptual reasons of designing studies. (1) Students explain why they measure certain variables and why they keep one or more variables constant in the experiment. (2) Students explain how the procedures will enable them to find out the answers to their research question. (3) Students provide explanations of their predictions
Explaining results: (1) identifying patterns from data, (2) dealing with anomalous data or flaws in experiments, and (3) developing and using theory to explain results	Students follow procedures in identifying patterns and developing theories. The rationale behind the procedures is not discussed. Anomalous data or flaws in experiments are often treated as random or measurement errors	Students analyze data and use the analysis results to answer their research questions. (1) Students design tables to record data, create graphs to represent data, and identify patterns based on the tables and graphs. (2) Students discuss how to deal with anomalous data or flaws in experiment. They consider whether their predicted theory/ model should be kept, modified, or transformed. (3) Students use the theory to explain the results. Their explanations should contain reasoning

idea that force causes motion. This idea is very different from the scientific understanding that associates force with acceleration (i.e. changes in velocity/motion). Second, students' reasoning is usually *vague and idiosyncratic*, and therefore does not allow fine-grained differentiations. For example, students often confuse work and energy, whereas scientific reasoning about the work–energy theorem recognizes that work and heat are process variables, while energy is a status variable (Loverude, Kautz, & Heron, 2002).

Therefore, we identify disciplinary reasoning, the specialized ways of reasoning behind science concepts and principles, as a second important competency that should be developed in science classrooms. The literature about conceptual change and misconception provides rich information regarding how students' intuitive ideas differ from the disciplinary reasoning. In particular, the 'Research Base' of *Benchmarks for Science Literacy* (American Association for the Advancement of Science, 1993) provides summaries of students' misconceptions about important concepts and principles in science disciplines.

Social aspect of inquiry: how should science be taught

We expect students to master scientific skills and scientific knowledge. However, the cognitive processes underlying the scientific skills and the reasoning behind the scientific knowledge are very challenging for students. NSES emphasizes that students must learn inquiry within their developmental capabilities (NRC, 1996). Thus, inquiry in science classrooms often requires guidance (NRC, 2007) and the degree of guidance may vary (NRC, 2000). Teachers' discourse can play a significant role in scaffolding students to develop the cognitive processes and disciplinary reasoning. Indeed, the verbal interactions among students and between the teacher and students are a significant indicator of students' engagement in inquiry (Krystyniak & Heikkinen, 2007). The literature on classroom discourse suggests that two dimensions of classroom discourse are critical in promoting authentic scientific inquiry: students' opportunities to talk, and interaction patterns.

Students' opportunities to talk

Classroom discourse can be interactive when the teacher interacts with students, or non-interactive when the teacher is the only person who does the talking (Mortimer & Scott, 2003). In traditional science classes, the teacher usually dominates discussions. In inquiry-based classes, there are usually more interactions between the teacher and students. Moreover, inquiry-based lessons usually involve more interactions among students themselves (e.g. teacher–student–student, teacher–student–student–student, and sudent–student) (McNeill & Pimentel, 2010). Therefore, we investigate *students' opportunities to talk* by examining to what extent students were involved in the classroom talk.

Interaction patterns

The quality of interactions also matters. How do teachers interact with students? Are students' views discussed in class? How are different views discussed? Mortimer and Scott (2003) propose that classroom discourse can be authoritative or dialogical, depending on either one perspective or multiple perspectives being discussed. To this end, researchers have identified different interaction patterns. In traditional science classes, a dominant interaction pattern is I–R–E, where the teacher initiates a dialogue with a question (I), a student responds to the question (R), and the teacher provides evaluation for the student response (E) (Lemke, 1990). I–R–E presents the teacher's perspective as a single authoritative perspective in class. Discourse patterns in inquiry-based lessons are very different. One example is an I–R–P–R chain (i.e. I–R–P–R … R or I–R–P–R–P … E), in which the teacher uses prompts (P) to continuously encourage students to explain and elaborate upon their ideas (Aguiar, Mortimer, & Scott, 2010). This interaction pattern suggests that teachers include students' ideas and perspectives in discussions. As another example, open-ended questions are more effective than closed questions in eliciting students' ideas (McNeill & Pimentel, 2010). Building upon these ideas, we identify *interaction patterns* by examining how the verbal interactions in class allowed students to discuss their perspectives.

In summary, we sought to investigate how expert and senior Chinese physics teachers use classroom discourse to promote the cognitive and social aspects of inquiry. Our conceptual framework was developed based on two bodies of literature. The literature on inquiry-based teaching and learning provides ideas about what should be taught from a cognitive aspect. It suggests the importance of developing two competencies in science classrooms: cognitive processes underlying the scientific skills and disciplinary reasoning behind the scientific knowledge. The literature on classroom discourse provides ideas about how science should be taught. It highlights the importance of providing students with opportunities to talk and using dialogical interactions. We, therefore, integrated ideas from both bodies of research into a unified conceptual framework that addresses both the cognitive aspect and the social aspect of inquiry.

Methods

Participants and data collection

Our data were collected from two sources. First, 12 videos were selected from the videos collected by the Chinese Association of Physics Education (CAPE). CAPE held an annual *National Physics Teaching Master Contest* from 2009 to 2014. Inquiry was the main theme of the contests. Senior teachers across the country were invited to teach self-designed inquiry lessons. A committee consisting of university professors and expert teachers observed and evaluated the lessons. The fourth author of this article was one of the experts in the committee. We watched the videos that were evaluated by the committee as demonstrating high-quality inquiry-based teaching. We watched 60 videos and selected the ones that used at least one-third of class time for whole-class discussion, as our focus is on classroom discourse. We also made sure that each core content topic of secondary school physics classes was included in the selected videos. As a result, 12 videos were selected. The teachers of these lessons all had a B.S. degree in science education and a professional title of senior teacher. Their experience ranged from 7 to 23 years of teaching. They were from 12 'key' urban schools during the time of teaching the inquiry lessons. Key urban schools use entrance examinations to select students based on the students' academic performance. Compared to rural, suburban, and other urban schools, key urban schools usually have more resources, and their students usually demonstrate higher performance on standardized tests.

Second, the second and the fourth authors observed and video-recorded inquiry lessons from five expert teachers. Most of these expert teachers were the members of the CAPE teaching strategy consultation committee. Some of them were also invited as consultants for the revision of the national curriculum standards. Their teaching videos have been used as exemplar cases in preservice teacher education programs in several universities. These teachers had 16–23 years of teaching experience and had a national reputation for excellent teaching. They designed these lessons based on their past teaching experience and their interpretation of and experience with inquiry. Information on the lesson videos and participant teachers are presented in Table 2. Each lesson lasted 40 minutes.

Data analysis

For each lesson video, we analyzed whole-class discussions. We first segmented these episodes into three different grain-sizes, using a video analysis software, Camtasia Studio 8 (TechSmith, 2012):

Table 2. Data sources.

Teachers	Topic of the lesson	Grade level	Years of teaching	Total minutes for whole-class discussion
Senior 1	Electromagnetic wave	Grade 11	12	19
Senior 2	Voltage	Grade 11	9	17
Senior 3	Ohm's Law	Grade 11	10	18
Senior 4	Newton's Second Law	Grade 10	11	12
Senior 5	Lenz's law	Grade 11	8	15
Senior 6	Newton's First Law	Grade 10	12	22
Senior 7	Electric Field	Grade 11	7	14
Senior 8	Law of Universal Gravitation	Grade 10	10	18
Senior 9	Conservation of Mechanical Energy	Grade 10	9	19
Senior 10	Projectile Motion	Grade 10	11	13
Senior 11	Mechanical Wave	Grade 11	8	14
Senior 12	Electromagnetic Wave	Grade 11	7	16
Expert 1	Acceleration	Grade 10	16	23
Expert 2	Work and Energy	Grade 10	21	27
Expert 3	newton's first law	Grade 10	23	22
Expert 4	Newton's Third Law	Grade 10	18	20
Expert 5	Coulomb's Law	Grade 11	14	21

- *Turn.* A turn contains one or more utterances, by which one person holds the floor in the conversation (Sack, Schegloff, & Jefferson, 1974). We found that, in classroom conversations, a turn from a teacher may sometimes contain utterances that have different functions. For example, a teacher may first provide an evaluation to a preceding student response and then pose a new question immediately after the evaluation. In situations like this, we divide the teacher's talk into two consecutive turns because two 'speech acts (Searle, 1969)' were involved—the first turn suggested an act of evaluation, whereas the second turn implied an act of initiating a new conversation.
- *Exchange.* While turns are a unit for analyzing one person's speech acts, exchanges are the smallest unit for analyzing conversational interactions among people. Usually, an exchange contains two or three turns, including a first turn initiating a dialog (initiation), a second turn responding to the first turn (response), and possibly a third turn that either evaluates/confirms the second turn or expands the ideas of the first/second turn (Jacobs & Jackson, 1982; Lemke, 1990; Mortimer & Scott, 2003). In this study, we found that an exchange could be longer than three turns, because the teachers sometimes asked follow-up questions to further elicit students' ideas. Therefore, we included follow-up questions and responses as part of a discourse exchange.
- *Sequence.* A sequence is a chain of exchanges. These discourse exchanges build upon each other to complete a task or a discussion topic. For example, a teacher may use a sequence of three discourse exchanges to scaffold students in comparing forces in three different situations: stationary, constant velocity, and constant acceleration. In this sequence, each exchange is about one situation.

The segmentation resulted in a total of 958 turns, 206 exchanges, and 168 sequences. Among the 168 sequences, 100 sequences are content sequences, which are discussions of scientific content knowledge. The remaining 68 sequences are about scientific methods (e.g. set-up of a lab device) and are not tied to the definitions, meanings, or application of specific science concepts, principles, or ideas.

Next, we conducted an analysis for the two inquiry competencies (i.e. cognitive processes and disciplinary reasoning). In this process, we used *sequence* (i.e. *a set of discourse exchanges used to complete a learning task*) as the unit of analysis. For cognitive processes, we analyzed all 168 sequences. For disciplinary reasoning, we analyzed 100 content sequences, because disciplinary reasoning is specific about science content. The data analysis contains three steps:

- *Developing preliminary coding schemes.* For cognitive processes, we developed a preliminary coding scheme based on the scientific skills and underlying cognitive processes presented in Table 1. For disciplinary reasoning, we used a constant comparison method (Glaser, 1969) to identify different discourse patterns. We used those patterns to generate a preliminary coding scheme.
- *Developmental coding.* In the second step, we used an iterative process to revise the coding schemes, and by doing so enhanced the validity. In the first cycle of the developmental coding, three raters used the coding scheme to independently code three lessons. Disagreements of coding as well as other issues were discussed and resolved through revising the coding scheme and training raters. In this process, new codes were often generated to describe emerging patterns. In the following cycle, the three raters used the revised coding scheme to recode the three lessons and code two additional lessons. The developmental coding repeated until the raters reached 85% agreement and the data saturation occurred—no new patterns were observed in the data (Guest, Bunce, & Johnson, 2006).
- *Final coding.* In the final step, the three raters used the revised coding schemes to code all remaining lesson videos. We performed Fleiss' kappa to measure interrater reliability. The Fleiss' kappa (Gwet, 2014) was 0.89 and 0.93 for cognitive processes and disciplinary reasoning, respectively. Then, the researchers and the raters discussed the discrepancies and reached agreement on the final codes.

Next, to examine how science was taught in class (i.e. students' opportunities to talk and interaction patterns), we used exchanges as the unit of analysis because this unit is small enough to allow us to capture the moment-to-moment dynamics of interactions in class discussions. Using the same approach described above, we analyzed 206 exchanges. Fleiss' kappa was performed to measure interrater reliability. The reliabilities were 0.91 and 0.92 for students' opportunities to talk, and interaction patterns, respectively. Then the researchers and the raters discussed the discrepancies and reached agreement on the final codes.

Findings

In this section, we report on how senior teachers and expert teachers structured inquiry-oriented classroom discourse. The ultimate goal of this study is to identify salient patterns of inquiry-based teaching of Chinese physics teachers, and by doing so, provide important implications for professional development and teacher education programs. Therefore, we report patterns of inquiry-based teaching across all teachers' lessons. As the sampling (12 senior teachers and 5 expert teachers) does not allow an appropriate comparison, we do not intend to compare the two groups of teachers.

The cognitive aspect of inquiry: what were taught

Cognitive processes behind scientific skills

We analyzed 168 sequences to investigate how frequently the teachers taught the scientific skills. Table 3 presents the numbers of the sequences that were about discussions of different scientific skills. Figure 2 presents the percentages of the sequences about different scientific skills in all teachers' lessons. The results show that the teachers discussed 'developing and using theories' most frequently and three skills (planning procedures, identifying patterns from the data, and dealing with anomalous data or flaws in experiment) least frequently.

When discussing scientific skills, teachers may or may not help students develop the cognitive processes behind the skills. For example, in one senior teacher's class on Ohm's law, the teacher asked students to connect a circuit in a certain way. She especially emphasized that the voltmeter should be connected to the resistor in parallel. However, she did not explain why or ask students to explain. In this case, the skill of planning procedures (connecting a circuit) was discussed, but the underlying cognitive process (why voltmeter should be connected in parallel) was not.

The excerpt below is an example of developing cognitive processes. It is from a senior teacher's lesson. The lesson is about the experiment of verification of Newton's Second Law. The setup of the experiment device is presented in Figure 3.

T: Is there anything you don't understand about the design of this experiment [verification of Newton's Second Law]?
S: Why do we have to put the cart on a plane that is a bit inclined?
T: *We do this in order to cancel the force exerted on the cart by paper tape and other resistances. As a result, the cart can move at a constant speed, when we don't put weights at the end.*

After a student raised a question about the setup of the device, the teacher provided answers directly. The cognitive process behind the skill of planning procedures (i.e. an inclined plane was used to cancel the resistance force) was taught, although not through inquiry—the teacher did not encourage the students to explore the question.

Since the teachers discussed 'developing and using theories' most frequently, we provide an example to show how a teacher taught the cognitive process behind this

Table 3. Scientific skills taught in the lessons.

		Expert teachers	Senior teachers	All teachers
Generating Questions	Generating research questions	18	12	30
Designing Studies	Controlling variables	6	8	14
	Making predictions	2	15	17
	Planning procedures	2	8	10
Explaining Results	Identifying patterns from the data	1	9	10
	Dealing with anomalous data or flaws in experiment	2	9	11
	Developing & using theories	34	42	76
	Total	65	103	168

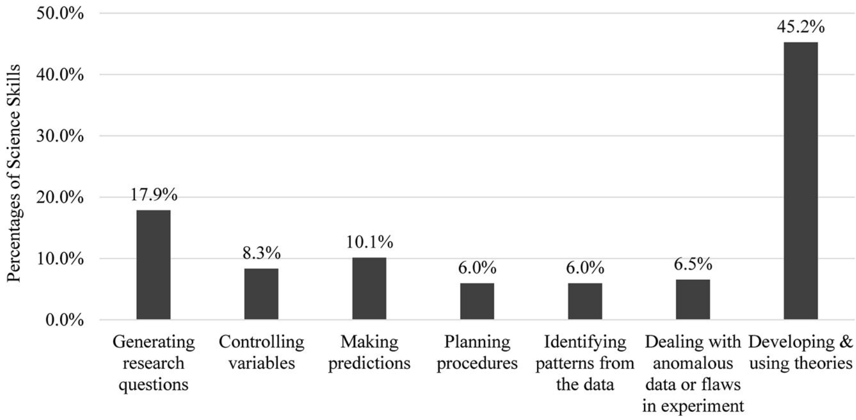

Figure 2. Sequences used to discuss scientific methods in all teachers' lessons ($N = 168$).

scientific skill. In the example, a senior teacher helped students develop the concept of magnetic field. The students worked in pairs. They held a magnet close to some steel nails on the table and observed what happened.

T: Can you describe your observation?

S1: The magnet picked up the nails.

T: How about other students? Did you observe the same phenomenon? Can you provide more details?

[No response]

T: When did you see the nails moving? After the magnet touched them? Before the magnet touched them?
Students: Before.
… …
T: Now, place your finger close to the nails. OK. Did you finger pick up the nails?
Students: No.

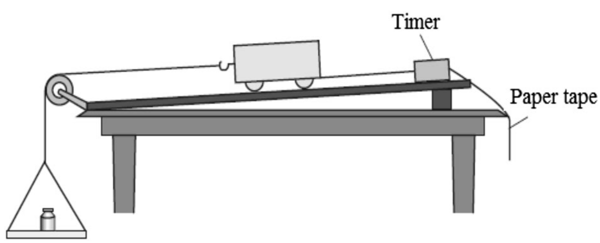

Figure 3. Setup device of the experiment.

T: OK. Looks like the magnet exerted a force on the nails from a distance, but your finger did not. Do you think the space around the magnet is the same as the space around your finger? Not the same? Can you tell me why you think they are different?
S: That is magnet. It is magnetic.
T: If the spaces are the same, we should have observed the same phenomenon. So, what exactly is surrounding a magnetic object? Actually, scientists conducted many experiments. They found that a special field surrounds a magnet. They call it magnetic field. … …

In the above excerpt, the students observed what happened when a magnet and a finger were placed close to some steel nails. The class discussion focused on why a magnet picked up nails from a distance, but a finger did not. Toward the end of the discussion, the teacher explained that scientists created the concept of magnetic field to explain magnetic phenomena such as those the students had observed. In this case, the teacher guided the students through a process of formulating theories from observations. Therefore, the cognitive process of developing theories is taught, although not in a way that provided students enough opportunities to talk.

We examined how frequently the teachers discussed the cognitive processes when teaching the scientific skills. Figure 4 shows that the teachers discussed the cognitive processes underlying the scientific skills in about half of the conversation sequences. This evidence suggests that the teachers in general recognized the importance of teaching the rationale and thinking behind scientific skills.

Disciplinary reasoning behind science content

Regarding disciplinary reasoning, we analyzed 100 content sequences (i.e. conversation sequences that are about science content). We found four patterns: informal statements, informal reasoning, scientific statements, and scientific reasoning.

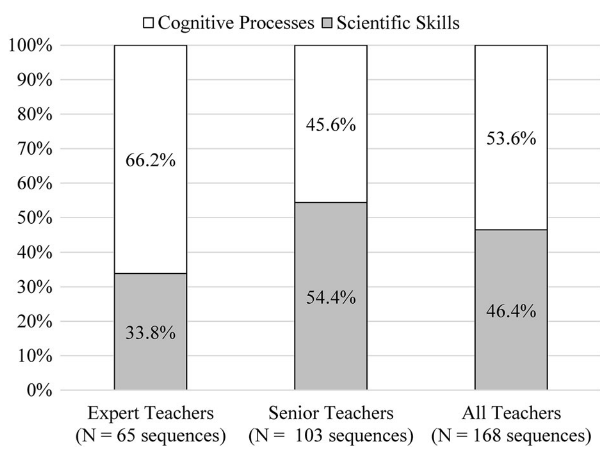

Figure 4. Cognitive processes taught in class.

In *informal statements* sequences, the teacher or a student provided an informal conclusion or claim, but there was no discussion about the underlying reasoning or rationale. For example, in a senior teacher's lesson, the teacher asked, 'Do you know why the magnetic needle changed its direction when we put it close to the circuit?' A student provided an informal idea, 'Electric current is flowing in the circuit. It has "electricity force".' The teacher said, 'OK.' She did not ask the student to explain what electricity force meant. Neither did she mention that response in the following discussions.

In *informal reasoning* sequences, the reasoning and rationale behind informal statements are discussed. Below is an example.

T: Today, we are going to examine an object. This is an object. I'm holding the object, keeping it at rest. We know that two forces are exerted on it, gravity and the normal force. So, how does gravity compare to the normal force in terms of magnitude?

S1: The same

T: Now, I hold the same object, but I keep it moving at a constant speed in the same direction, the horizontal direction. What is the relation between gravity and the normal force?

S2: The same.

T: Now, I hold the same object, but I keep it moving upward at a constant speed. What is the relation between gravity and the normal force?

S3: The normal force is bigger.

S4: The same.

Many other students: the same.

T: The same. Why did we hesitate when providing this answer? Who can tell me the reason? How about you? [pointing to S3]

S3: It's moving upward, so I think the upward force should be bigger.

T: OK. *Because of the existence of friction, our life experience often misleads our thinking. If you pull an object, it will move. If you don't pull it, it will not move. In this situation, because we are lifting the object upward, of course the upward force is bigger than the downward force.*

In the excerpt above, an expert teacher asked the students to compare the normal force and gravity in two conditions: an object staying at rest and an object moving upward at a constant velocity. Toward the end of the discussion, the teacher used two examples to explain how people construct intuitive ideas based on their life experience: pulling an object and lifting an object. In both examples, people assume that force causes the motion.

In *scientific statements* sequences, the teacher describes the scientific concepts, principles, and facts without reference to the reasoning behind them. For example, when introducing the concept of acceleration, a senior teacher told students that a physics principle related to acceleration is Newton's Second Law. Then, he continued to provide the statement of Newton's Second Law.

In *scientific reasoning*, the teacher discusses the specific ways of reasoning behind scientific knowledge. The excerpt below is an example. After the students finished watching a video about Newton's First Law, the teacher asked the students to provide conclusions.

T: You have watched the video (a video about Newton's First Law). Based on the video, what conclusions can you make?

S1: Objects will keep moving if there is no external force.
S2: No. I think objects will stop slowly because objects always stop moving eventually.

T: OK. *Let's consider three conditions, an object moving on a carpet, an object moving on a relatively smooth surface, and an object moving on ice. What will happen to these three objects?*

S3: The object will move farther and farther away in the order of the three conditions.

T: Why do you think so?

S3: Because the friction is smaller and smaller, when we compare the three conditions.

T: *Now, consider a condition where there is no friction, what will happen?*

S4: The object will keep moving.

In the above excerpt, two students disagreed with each other. S1 provided a scientific statement of the First Law, while S2 provided a conclusion that was based on everyday experience: Objects will stop moving because they always do. To help students understand the scientific reasoning behind the statement of the First Law, the teacher asked students to compare motion under three conditions: on a carpet, on a relatively smooth surface, and on ice. In this process, the teacher used questions to guide students to infer that the friction force was getting smaller across the three conditions. Then, the teacher asked the students to infer what would happen in an ideal situation where friction was zero. Students, therefore, inferred a conclusion that is aligned with the First Law: An object in motion stays in motion unless acted upon by an unbalanced force. In the history of science, Galileo used the same logical thinking to derive the concept of inertia in his famous thought experiment about rolling balls on inclined planes.

The distribution of the four patterns of teaching disciplinary reasoning is presented in Figure 5. Figure 5 suggests several important patterns. The first pattern is about how the teachers explained science concepts and principles (bars in the solid-line rectangle). To foster meaningful science learning, we expect teachers to discuss with students the scientific reasoning behind content. However, in a traditional science class, the instruction may focus on

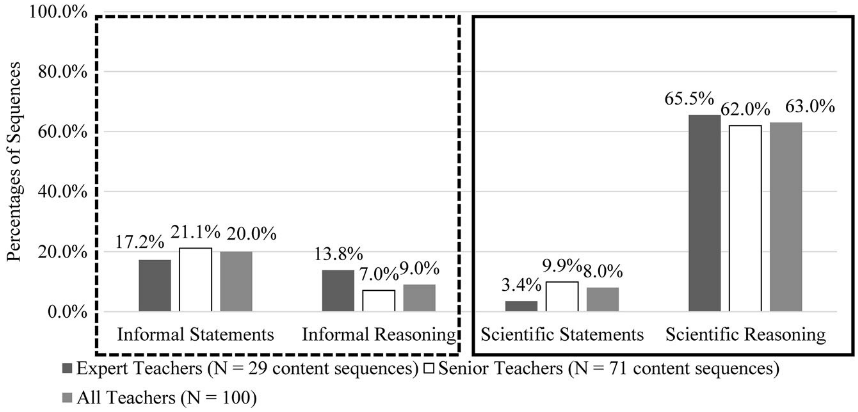

Figure 5. Teaching disciplinary reasoning in classroom.

evaluating how well students recite scientific statements (Lemke, 1990). A comparison between the percentages of sequences in scientific statements and those in scientific reasoning suggests that the teachers in both groups demonstrated consistent habits in helping students understand the reasoning behind science content. The second pattern is about how the teachers discussed intuitive ideas (bars in the dashed-line rectangle). Helping students to be aware of the rationale behind their informal ideas is very important for promoting conceptual learning (Anderson & Smith, 1987). Therefore, we expect teachers not only to mention common intuitive ideas, but also to explicitly address the rationale and reasoning behind those intuitive ideas. A comparison between the percentages of sequences in informal statements and those in informal reasoning suggests that the teachers sometimes mentioned students' intuitive ideas, but they were very unlikely to discuss the underlying rationale and reasoning behind those ideas. The third pattern is about the comparison between discussions about science and discussions about intuitive ideas (comparison between the two rectangles). Figure 5 suggests that students' informal ideas were discussed much less frequently than scientific ideas. As shown in the above discussion about Newton's First Law, the teacher guided students in using a thought experiment to understand the reasoning behind the statement of the First Law. However, she missed an opportunity to address a student's informal idea. During the discussion, a student proposed an idea that all objects will stop moving eventually. The teacher did not explicitly talk about how that idea was developed from everyday experience. Together, the above patterns may reflect a common view of science learning in Chinese schools that scientific knowledge and reasoning should be used to replace students' informal ideas, and this can be done by clearly explaining the logic behind the content.

The social aspect of inquiry: how science was taught

We examined *how* cognitive processes and the disciplinary reasoning were taught in science classrooms in terms of (1) students' opportunities to talk and (2) interaction patterns. Altogether, we analyzed 206 conversation exchanges.

Students' opportunities to talk

We identified three patterns regarding students' opportunities to talk. In *teacher's talk*, the teacher did not solicit any responses from the students, and students responded to teachers' talk by listening, taking notes, and so on (T). In *teacher–student interactions*, the conversation happened between the teacher and the students (e.g. TS, TST, and TSTS), and there were no interactions among the students. In *students' interactions*, the conversation involved interactions among students (e.g. SS, TSS, TSSS, and TSTSS). As shown in Figure 6, the results indicate that the teachers in general included students in the classroom conversations. However, discussions among students were less frequent, especially in senior teachers' lessons.

Interaction patterns

We identified interaction patterns and ordered those patterns into three levels of student engagement. At Level 1, the teacher is the authority, who asks questions and provides evaluations. Level 1 contains two types of exchanges: Closed Question—Response—Evaluation (CRE or CR) and Open Question—Teacher Answers (OT). In CRE and CR interactions, the teacher asks closed questions (i.e. questions requiring recall of textbook knowledge such as 'yes or no' questions, filling-the-blank questions, and providing definition type of questions), students provide responses (R), and the teacher may or may not evaluate students' response (E). In OT interactions, the teacher asks an open-ended question (O) and provides answers to that question immediately (T). At Level 1, the knowledge from the textbook was presented as authoritative knowledge and the teacher is the authority to transmit that knowledge in the classroom. Level 1 interaction patterns are similar to the traditional IRE interaction (Lemke, 1990).

At Level 2, students express their ideas, but the teacher does not further elicit or scaffold student thinking. Level 2 contains Open-ended Question—Student Response—Teacher Evaluation (ORE or OR). In ORE or OR interactions, the teacher asks an open-ended question (O), and the students provide responses (R). Then, instead of leading students to reflect on their own responses, the teacher provides an authoritative evaluation of students' responses (E). Or, the teacher may not provide any feedback. At Level 2, the teacher encouraged students to provide their opinions, but the teacher is still the authority to provide evaluation. An example of Level 2 interaction pattern is provided below.

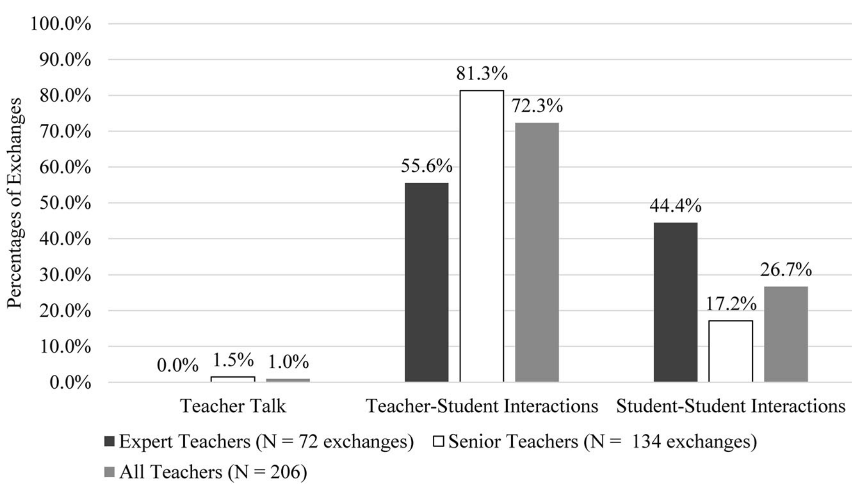

Figure 6. Students' opportunities to talk.

T: In the experiment, we observed that the red end of the compass needles moved. So, we know that there is a special kind of entity around the bar magnet. How do you understand the meaning of special type of entity? How is it special? Please. (O)

S1: Because although we cannot touch it, it really exists. (R)

T: OK. *It is special because we cannot see it or touch it, right? OK. Please sit down. In addition to this, air is also something we cannot see or touch, but we never say that it is a special entity. So, the magnetic field is special because it is not made up of atoms or molecules.* (E)

In the excerpt above, a senior teacher asked students to explain why field was a special entity. After the student provided a textbook answer, the teacher first confirmed the student's response, and then further elaborated that field was special because it was not made up of atoms and molecules. Instead of asking the student and her peers to think about the distinction between field and other entities such as air, the teacher provided a scientific explanation directly.

At Level 3, students express their ideas, and the teacher scaffolds the students to further reason about scientific content or scientific practices. The interaction patterns are ORPR … and ORPR … E. An important characteristic of Level 3 interactions is that the teacher uses probing questions (P). In ORPR … and ORPR … E interactions, the teacher asks an open-ended question (O), the students respond to the question (R), and the teacher asks a follow-up *probing* question based on the meaning of the student's previous response (P). The teacher may also provide an evaluation or explanation at the end (E). ORPR … and ORPR … E interaction patterns are similar to those that Mortimer and Scott (2003) discovered in their study. Below is an example of ORPR … E interactions.

T: Now, I lift the object to a higher position. Do you think its energy will change? Ok, you go ahead and talk. *What's your opinion? (O)*

S1: I don't think its energy will change. It's still the same thing. No matter where it is, its energy does not change. (R)

T: *Now, I'm going to do an experiment. [The teacher held a book right above a student's head; the book was at a low position] If I put it here, what do you feel? [The teacher then raised the book to a higher position above the student's head.] If I put it here, what do you feel? (P)*

Students all laughed. (R)

T: Let's see. What's her experience tell us? Could you please let us know why did you tremble? (P)

S2: If it falls, it will hit me and it hurts. (R)

T: Why do you think it would hurt you? Is it because holding it at this position [high potion] and at this this position will lead to different results? (P)

S2: Yes. (R)

T: Why would it hurt? (P)
S: Because the velocity would be much greater. (R)
T: What does it tell us? (P)
S: The object has more energy. (R)
T: OK. What does it tell us regarding the same object in a higher position? (P)
S: It must also have more energy. (R)
T: OK. The relationships between position and energy. (E)

In the above excerpt, an expert teacher was discussing about gravitational energy with his students. The teacher asked the students to provide their opinions on the relationship between energy and the position of an object. S1 claimed that energy would not change because energy does not change no matter where the object is. It appeared that the student might apply the law of energy conservation (i.e. Energy cannot be created or destroyed.) without reasoning about the mechanism in the specific context. In addition, the student did not demonstrate a correct understanding of the law. He did not recognize that gravitational energy is associated with the height of an object. To scaffold the students, the teacher did a simple experiment, in which he held a book at different heights above a student's head. The teacher asked the students to compare what would happen when the book fell in these two conditions. He used several probing questions to guide the students in using the concept of gravitational energy to explain the effects of free fall of the book in the two conditions.

The percentages of the exchanges at each level are presented in Figure 7. The results show that about 52.4% of conversation exchanges were coded as Level 2 and about 38.8% of conversation exchanges were coded as Level 3. This evidence suggests that the teachers in general recognized the importance of encouraging students to talk about their ideas, but they need to develop more effective strategies for doing that.

Conclusions and implications

During the current curriculum reform movement beginning in 1999, most schools across mainland China have adopted the new National Science Education Curriculum Standards. The curriculum standards reflect a vision that places inquiry as the driving force for learning scientific knowledge and methods. Although inquiry has been the central focus of the curriculum reform, very few empirical studies have investigated how inquiry was carried out in science classrooms. This study contributes to this reform effort by investigating how Chinese physics teachers structured classroom discourse to support students' inquiry-based learning. Our participants were physics teachers who were actively involved in teacher education and professional development activities. Some of their lesson videos were used as exemplar lessons to support preservice and in-service teachers' learning to

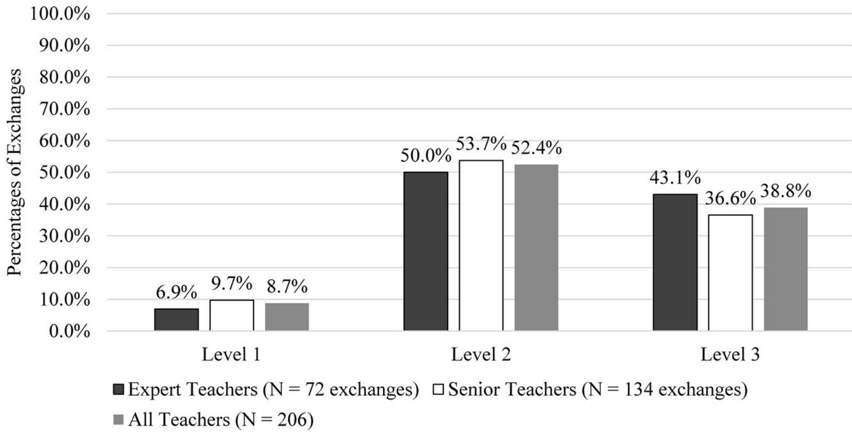

Figure 7. Interaction patterns at each level

teach inquiry. Therefore, identification of the strength and weaknesses of these teachers' teaching provides significant implications for teacher education and professional development.

Although the lesson videos to a certain degree represent the best teaching practices in China, our analysis of the videos uncover both promises and problems. Regarding the cognitive aspect of inquiry, the teachers in general recognize the importance of teaching the cognitive processes and disciplinary reasoning behind the scientific knowledge and skills. The results show that the teachers discussed the cognitive processes behind scientific skills in more than half of the sequences. When teaching science content, they often addressed the disciplinary reasoning behind concepts and principles. However, they were less likely to address common intuitive ideas about science concepts and principles in class. This is an important issue because there is a consensus in the science education community that conceptual learning of science only happens when instruction attends to students' intuitive ideas, reasoning, and thinking (Anderson & Smith, 1987; Posner, Strike, Hewson, & Gertzog, 1982). Therefore, we suggest that teacher education and professional development programs support teachers in analyzing and interpreting common intuitive ideas of students, and in using formative assessments to elicit student thinking.

Regarding the social aspect of inquiry, the results suggest that the teachers recognized that it is important to interact with students in class. However, it appeared that facilitating conversations among students and prompting students to talk about their own ideas are challenging, especially for the senior teachers. This finding is similar to what Sun and colleagues found in their study on secondary integrated science lessons (Sun, Wang, Xie, & Boon, 2014). They found that the teachers usually dominated classroom conversations and inquiry activities were rare. Therefore, we suggest that teacher education and professional development programs provide teachers with strategies that facilitate students to communicate with each other and to express their own ideas.

Unlike their peers in Western countries, Chinese teachers usually lack resources and supports in developing and implementing inquiry-based teaching in their classrooms. Zhang and his colleagues (Zhang et al., 2003) conducted a large-scale survey study and found that although most participants were enthusiastic about inquiry, they faced significant challenges such as the pressure of national college entrance exams, transforming traditional curriculum, and equitable distribution of inquiry resources across urban and rural schools. To help teachers overcome the weaknesses identified in this study and to improve teaching in general, it is important that policy-makers and teacher educators consider teachers' concerns and provide necessary supports and resources.

It is important to note that this is a qualitative study with a small sample size. Therefore, the results of the study cannot be generalized to an institutional or national level. However, the conceptualization of inquiry in a Chinese context and the results about how Chinese physics teachers taught self-designed inquiry lessons will contribute to the foundation for conducting large-scale video studies such as those carried out in the Trends in International Mathematics and Science Study (TIMSS) (Roth et al., 2006). Moreover, large-scale quantitative video studies often report on patterns that can be easily identified and quantified across class videos such as how much class time was spent in classwork and seatwork, whether first-hand data were used, and whether the conceptual reason for conducting experiments was discussed (Jacobs, Kawanaka, & Stigler, 1999; Roth et al., 2006). The dynamics of teacher–student interactions captured in this study are complementary to such findings from large-scale research.

Notes

1. In China, K-12 teachers progress through professional ranks, including junior teacher, senior teacher, and expert teacher, based on their teaching performance and years of teaching.
2. There are 31 province-level administrative divisions located in mainland China, including 22 provinces, 4 municipalities, and 5 autonomous regions.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was supported by the Ministry of Education of China, under the Humanity and Social Science Foundation [13YJA880022]; and Education Testing Service under the CBAL (Cognitive Based Assessment by, for, and of Learning) Initiative.

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