Educational research

Identifying pedagogical content knowledge (PCK) in the chemistry laboratory

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Abstract: This study was carried out in the chemical teaching laboratory with new graduate students while they were guided to develop pedagogical content knowledge, PCK. PCK is expertise that demonstrates a combined knowledge of pedagogy and disciplinary subject matter; since *chemistry* is the discipline, the abbreviation, P*Ch*K, is used. Laboratory teaching functions for student learning entail guidance of chemical techniques, and abstract chemical concepts relevant to the lab experiment, that is, chemical explanations using concepts *conceived* by chemists rather than perceived, e.g., atoms and chemical bonds. Instruments were built with constructivist content and attained construct validity and internal consistency to measure teaching performance. A factor analysis reduced fifteen constructs to three forms of P*Ch*K, whose names reflect the level of chemical knowledge and pedagogical sophistication required. Mentoring activities were labeled as P*Ch*K-0. P*Ch*K-1 represents procedural knowledge to manage a chemistry laboratory. P*Ch*K-2 represents devising or generating *transforming explanations* connected to the students' knowledge and previous experiences. A 'transforming explanation' is defined as a discipline-specific illustration of how people in that discipline think about a disciplinary process, which is linked by the explanation to students' thinking about that same disciplinary-related process. P*Ch*K-3 guides students in chemistry-specific reasoning and generating transforming explanations for themselves. Examples of P*Ch*K-2 and P*Ch*K-3, using two chemical topics, are provided. [*Chem. Educ. Res. Pract.*, 2005, **6** (2), 83-103]

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Introduction: Pedagogical Content Knowledge (PCK) in Chemistry

The science of chemistry provides chemical knowledge, some of which is designated subject matter to be taught at primary, secondary, tertiary, and graduate levels of education. Shulman (1986) defined pedagogical *content* knowledge (PCK) as interwoven pedagogy and subject matter knowledge necessary for good disciplinary teaching. Pedagogical content knowledge is considered to be craft knowledge, defined as "*integrated knowledge which represents the teachers' accumulated wisdom with respect to their teaching practice. As craft knowledge guides the teachers' actions in practice, it encompasses teachers' knowledge and beliefs with respect to various aspects such as pedagogy, students, subject matter, and the curriculum*" (van Driel et al., 1998, p. 674). Craft knowledge is acquired from prior education, the teachers' personal backgrounds, the teaching contexts, and through experience in the 'doing' of teaching. Therefore, the wisdom of craft knowledge produces effective behavior on the part of the teacher who possesses it. The military version of wisdom concerns utilization of both strategies and tactics and provides a metaphor to wisdom in teaching. Strategies involve long term directing and maneuvering forces and equipment into the most advantageous positions (Agnes, 1999); in teaching it is the directing and maneuvering of students, materials, and equipment in the classroom or laboratory, thus orchestrating and directing for the most effective environment for learning. Maintenance of the effective learning environment requires using the particular set of strategies each session; these manage the personal climate, guarantee proficient student work, enable peer learning and discussion, and provide opportunities to reason in the discipline, for examples. Tactics are skillful methods or procedures that meet local and short-range objectives. Tactics arise based on the particular topics to be taught; therefore, tactics may differ to some degree from topic to topic and change as the teacher acquires more knowledge of pedagogy, the students being taught, and the interrelationships of subject matter in the curriculum.

Craft knowledge is necessary at the tertiary level as well. Despite the absence of formal teacher training among most tertiary faculty, the craft knowledge of PCK guides the creation of a learning environment and guides a teacher's actions in teaching a specific subject matter. Thus craft knowledge is as relevant a concept to university level faculty and teaching assistants as it is to primary and secondary faculty. In large universities graduate students instruct chemistry laboratories in the undergraduate (UG) curricula. During the times that graduate teaching assistants (GTAs) work through the challenges of teaching chemistry labs, they develop pedagogical *chemical* knowledge (P*Ch*K) that drives their orchestration of the environment, the interactions with students, and the tactics to address the learning of a chemical topic. We will continue to use this abbreviation when referring to chemistry teaching. Interacting with students in strategic and tactical manners that provide an effective learning environment for the majority of students is part of the challenge of professional teaching practice. Shulman (2002) explains that the learning process begins with teacher's engagement with students: "*Critical reflection on one's practice and understanding leads to higher-order thinking in the form of a capacity to exercise judgment in the face of uncertainty and to create designs in the presence of constraints and unpredictability*" (p. 38). Just as each battlefield restricts the battle in certain ways and always necessitates responses to unpredictable events, so a learning environment requires appropriate responses in that the teacher flexibly confronts problem issues that arise, judges the salient features, and makes prompt decisions for the benefit of student learning.

The chemistry teacher at tertiary levels is one who teaches organic mechanisms, stoichiometry, kinetics, various aspects of thermochemistry, and many other topics, which is why pedagogical chemical knowledge (PChK) about specific topics is an important area for further research according to other chemical educators (Geddis, 1993; van Driel et al., 1998; Bucat, 2004). Ideally, Shulman (1986) says, the teacher will *transform disciplinary knowledge* to encourage understanding of meaning by his/her population of students. Transformation is an explanatory process that differs from giving an explicit *restatement* of the chemical view of a concept or theory and expecting students to remember it. Teachers must *figure out what it means* to transform chemical knowledge on specific topics that explains chemistry at the level of their students. When working to transform chemical definitions to meaningful explanations, the teacher is planning the tactics to use in a specific laboratory context. In a later section we will explicate what it means to transform chemical knowledge on a specific topic.

Our settings were chemistry labs (general chemistry and organic chemistry). Our current study of GTA development investigated P*Ch*K in greater detail for two reasons. We wished to outline features of important constructivist teaching and learning practices as well as to identify critical aspects of P*Ch*K that might generalize to teaching in any science laboratory or inquiry setting. We used factor analysis of survey data as an exploratory method to generate theory about pedagogical content knowledge. Exploratory factor analysis identifies the factor structure or model for a set of variables, which includes both establishing the number of principal underlying factors in the data and the pattern seen in the correlations of each variable to the factors identified (Kim and Mueller, 1978). The theory generated about critical aspects of P*Ch*K was then applied to our specific findings about GTA development in P*Ch*K.

Constructivist Teaching and Learning Practices

A model of teaching/learning as knowledge transmission/reception is the dominant mode of teaching (Gallagher and Tobin, 1987). The basis for *transmission of explicit knowledge* from expert to novice is the expectation that a learner will receive an organization of knowledge about a topic from another's understanding into his own understanding. Unfortunately, explicit transmission of knowledge from an expert rarely leads to deep understanding in the novice (Bodner, 1986). Having a constructivist model of learning demands that a teacher encourage students' efforts to understand the material so as to remember it. Having a model of knowledge transmission does *not* demand that teachers explicitly *push* students to reason, so this teaching practice can inadvertently reinforce memorizing rules, facts, algorithms and procedures. A mixture of transmission of knowledge, supplemented with attempts by the teacher to guide reasoning using the new information, is more likely to be effective for getting students to understand complex subject matter.

The meaning of abstract, unfamiliar concepts or scientific explanations is constructed from many forms of input. Some understanding is gained implicitly from experience. Guiding students in chemical reasoning helps them build meaning because they have to learn how concepts fit together in appropriate chemical ways. To reason effectively, a novice student will need to reorganize his own current knowledge and understanding in light of abstract chemical ideas not previously encountered or not previously understood. Explicit transmission of what we want students *to know* is efficient; however, when telling students 'to know,' teachers usually mean they want students to understand the ideas they transmitted rather than memorize what they said. Usually, in lecture situations interaction is lacking, thus it is often difficult to determine students' current levels of comprehension. The laboratory experience, therefore, assumes special importance for helping students to think through chemical concepts and explanations. Given that human reasoning is essential to generate meaning (Mead, 1917), and since getting the meaning of an idea and how other ideas connect are the bases of understanding, opportunities *for* individual and group reasoning are the *essence* of an effective learning environment for people. Meaning is constructed from active learning situations such as the following: doing work; attempting to solve problems; listening to or reading relevant information when it is needed; awareness of cultural rules, norms or standards as guides; from the back and forth, give and take of a personal conversation with relative experts[1] or with peers, or a larger discussion such as a group meeting; putting together a piece of writing; and even from conversing with oneself as in introspection.

P*Ch*K Development

The goal of professional teaching is that GTAs should take more professional initiative in promoting the learning of undergraduate students (UGs) in the laboratory environment. General teaching expectations and basic knowledge about teaching chemistry labs can be

[1] A relative expert is someone who knows more than another on a topic but is not considered an expert in the field.

transmitted to GTAs in the form of rules or lists of actions, such as producing a syllabus, giving a lab talk at the beginning, enforcing safety rules, and making sure students clean up after the lab. As a result of the need to gain teaching judgment, however, GTAs must adapt, reflect, and learn to appreciate and perform professional teaching strategies and tactics while they teach. In a teaching apprenticeship, modeling of teaching can occur by the instructor or advanced peers in real time or through video clips. The coaching provides specific direction and feedback to implement a high standard of work through key performance criteria. Weekly seminar discussions among peer GTAs provide communication in our teaching-apprenticeship course model. GTAs need to discuss emergent problems, problems they solved, knowledge they gained, and questions that an individual GTA wants to discuss with the group. Personal and professional discussions can create a teaching community similar to a research group, in that dialogue and feedback often foster introspection about individual work and its progress.

The survey findings of Abraham, Cracolice, Graves, Aldhamash, Kihega, Palma Gil and Varguese (1997) provided evidence that supports teaching practices that place more *emphasis on concepts* than procedural work in the laboratory environment. In their large study (268 American institutions responding, a 68% response) faculty were pressed to choose the most important laboratory-learning *goal* among the following: learning facts, laboratory skills, scientific processes, concepts or positive attitudes. Faculty chose *learning concepts* as the primary goal for UGs in a laboratory program. Since faculty members' primary lab goal for UGs is learning chemical concepts, then GTAs should perform with heavy emphasis on concept teaching.

Clearly the need in laboratory teaching is a balance between managing a chemical workplace and teaching chemistry, thus balancing procedural teaching and underlying concept teaching (Bond-Robinson and Rodriques, In press). In summary of our studies, qualitative analyses of video data demonstrated the practical manner in which high performing GTAs handled the balance between the procedural and conceptual teaching. The judgment that created the balance is craft knowledge gained in practice, which we call P*Ch*K. The following is a list of strategic approaches that exemplary GTAs used.

- Exemplary GTAs utilized all the time available *throughout* the lab session. Generally, the first half of the lab session concerned procedural knowledge and the opening conceptual overview. The UGs and GTA worked on aspects of procedures and on progressing into the experiment.
- Exemplary GTAs *orchestrated* the second half of the lab as well as the beginning parts. They started working with teams and pairs, explaining and probing UGs about chemically related meanings in their work.
- The exemplary GTA was strategic in conversations with students. Sometimes the GTA utilized explicit transmission of experimental information, e.g., when asked a questions, she decided it was best to tell the students what to do; other times the GTA tried to get UGs to reason about their lab work or procedural difficulties because she decided it would benefit them more to think the problem through.
- The exemplary GTA asked each group to write their results on the board for public display.
- The exemplary GTA often drew the students together for a discussion, at which time she pointed out results, asked questions about the meaning of results, summarized class results in discussion, and gave UGs time to discuss the significance of what they found.
- Exemplary GTAs led their UGs into reasoning about how their work and results related to chemical concepts and processes rather than merely lab procedures and concrete results.

Methodology

Problem

Our problem was to understand the facets of P*Ch*K as they emerged in chemistry teaching labs. We utilized our quantitative data from undergraduate students' (UGs') responses about their GTA's actions to provide the basis for determining a structure of factors in constructivist teaching practices. The purpose of a factor analysis is to discern the meaning that respondents give to items, particularly the relative meanings of all items. We asked, "*How is PChK identified and classified in the work GTAs perform while teaching UGs in the laboratory*?"

Summary of valid and internally consistent instruments

Two instruments were built, validated, and tested for internal consistency. The instruments that we built to measure P*Ch*K development were based on features of a constructivist-learning environment. One instrument was designed for the GTA instructors to use; the other was designed for the undergraduate students (UGs) to use in assessment of their teaching assistant. The instrument for the instructor was built first and then tested for several iterations. Then the UG assessment instrument was built from it. Both instruments contain the same twelve strategic interactions; these defined the performance criteria for GTAs. Instructors used their instrument to code remotely acquired audio-video observations of the lab section. The UGs' instrument (shown in the Appendix) contained an extra three items that broadened for students the meanings of respect and help, explanation and student-GTA discussions of troubleshooting. Both instruments were tested with the people for whom they were designed; internal consistencies of each instrument reached high Cronbach alpha measurements of .86 (instructors) and .95 (UGs rating their GTA). Information about the content and operational definitions is found in the Appendix. A full account of the methods in the course, the manner in which we built the constructivist assessments, and a copy of the instructors' instrument is found in Bond-Robinson and Rodriques (2005).

Data Reduction and Identification of Underlying Factors

We did a factor analysis of 245 UGs' responses to fifteen items about their GTA, which occurred at the end of the semester in the fourth iteration of the GTA course. Exploratory factor analysis identifies the factor structure or model for a set of variables, which includes both establishing the number of principal underlying factors and the pattern seen in the factor loadings (correlations of a variable to the factors). Factor analysis assumes that variables can be observed and measured, e.g., in our case the UG survey takers responded to the constructs within the UGs' instrument from their observations and contact with their GTA. Techniques of factor analysis also assume that the observable variables are linear combinations of some underlying *unseen* factors (Kim and Mueller, 1978).

The main purposes of applying a factor analysis technique to a data set are to reduce the number of variables and to classify them (Statsoft, 1984-2003). We used rotational strategies in SPSS *11.0* statistical software to get effective differentiation among the *loadings*. The UGs' instrument was shown to possess construct validity when theoretically similar constructs were similar in their loadings on the underlying factors, e.g. by the similarities in loadings on factors 1 and 2 of the interactions in Table 1-A. Dissimilar constructs were shown to be dissimilar in factor loadings, such as the contrast between probing and discussion interactions in Table 1A and respect and helpfulness interaction in Table 1D.

In addition, we used factor analysis as an exploratory method to generate theory about pedagogical content knowledge.

Results of the Factor Analysis

The manner in which variables loaded on these factors differentiated aspects of GTA performance that required chemical knowledge and those that did not. Table 1 shows how the fifteen variables in 245 student responses were reduced to two factors (with eigenvalues > 1) that explained 68.2% of the variance. Factor 1 had an eigenvalue of 9.17; Factor 2's eigenvalue was 1.07. Notice that numbers in the table illustrate that all the variables loaded on both factors to a greater or lesser degree. The analysis data also allows us to give meaning to the factor loadings. Analysis of the variables with the highest loadings on Factor 1 appear in Table 1-A and 1-B. Variables that load most heavily on Factor 2 begin with Respect 1, shown in Table 1-D. After much deliberation of the loadings, we concluded that the variables that loaded more highly on Factor 1 seem to be involved in *purposefully* teaching chemistry, albeit with differing strategies. We labeled Factor 1, therefore, 'pedagogical chemical knowledge'. The highest loading variables on Factor 2 identified it as mentoring or advising activities sensitive to the students (Table 1-D). We labeled Factor 2 'responsive mentoring'.

The fifteen constructs from the UGs' instrument are ordered in Table 1 by the magnitude of 'loading' on Factor 1. Variables in Table 1-A show similar magnitudes of loading on Factor 1 and similar loadings on Factor 2; these variables show covariation with each other; so we grouped them together and gave them a label. For example, those in Table 1-A were labeled 'prompts conceptual thinking in students'. Note that Table 1-A further identifies these constructs as a form of PC*h*K; those meanings will be discussed later. Another factor loading pattern is shown in Table 1-E: The variable of interaction, the last entry in Factor 1, had significant loading on both factor 1 (.527) and on Factor 2 (.526). This result was interpreted to mean that interaction is an important component of both factors.

Table 1 Factor Analysis on GTAs' teaching (parts A-E). Each part shows labels given to actions with similar loadings on Factors 1 and 2. Extraction method was 'Principal Component Analysis. Rotation Method: Varimax'. The two factors (Eigen value >1.0) explained 68.2% of the variance.

A.

Variable	Fac. 1	Fac. 2	Operational Definition	Label
Troubleshoot With Peers	..815	..233	Encourages us to discuss procedural problems together as a team.	Prompts peer conceptual thinking about experiment
Facilitates Reasoning	.800	.262	Stimulates our team to discuss chemical concepts underlying the experiment.	Prompts peer thinking about underlying concepts
Prompts Reasoning	.788	.292	Prompts me to think about chemical concepts when I ask questions.	Prompts thinking about underlying concepts
Troubleshoot By Reasoning	.750	.249	Encourages me to think through problems when mistakes are made rather than just telling me what to do.	Prompts thinking of acts or underlying concepts
Summary	In general, the GTA uses pedagogical content knowledge in these actions taken with UGs, indicating they are taking initiative to prompt their students to reason through the procedural or concept-related subject matter.			P*Ch*K -3

B.

Variable	Fac 1	Fac.2	Operational Definition	Label
Links Concepts	.719	.407	Links chemical concepts to lab procedure so that I can understand them.	Initiates thinking about underlying concepts
Concrete Explanation	.710	.403	Discussions of chemical concepts with me occur at the level of my knowledge and previous experiences	Initiates thinking about underlying concepts
Summary	In general, GTA uses pedagogical content knowledge to explain the procedural or concept-related lab work and link it to abstract chemical concepts in a manner that is related to their students' current understandings.			P*Ch*K-2

C.

Variable	Fac. 1	Fac. 2	Operational Definition	Label	
Advice	.705	.521	Comments are helpful to my work during lab.	Initiates Help	Procedural
Guidance	.690	.453	Comments on problems given at the level of my knowledge.	Initiates Help	Procedural
Aware	.654	.410	Notices I'm having difficulties and helps, even if I do not ask.	Initiates Help	Procedural
Short Talks	.630	.441	Short talks are clear and help me understand the experiment.	Initiates Help	Procedural
Summary	In general, GTA uses pedagogical content knowledge to advice and guide students about the lab procedures, techniques, instruments and necessary calculations.			P*Ch*K-1	

D.

Variable	Fac 1	Fac. 2	Operational Definition	Label
Respect 1	.299	.876	Is respectful of me as a person.	Responsive Mentor
Respect 2	.377	.800	Is respectful of my knowledge and ability to learn.	Responsive Mentor
Helpful	.434	.709	Helps me when I ask for help.	Responsive Mentor
Safety	.186	.686	Models safety and other rules and enforces them.	Responsive Mentor
Summary	In general, GTA uses no content knowledge, indicating they are respectful of students and helpful. While we understand that predicting safe conditions requires chemical knowledge, we assume that students believed the lab is safe or it would not be part of the curriculum.			General Mentor

E.

Variable	Fac. 1	Fac. 2	Operational Definition	Label
Interaction	.526	.627	Interacts with us throughout the lab.	Fits strongly into both factors; thus a part of Mentor, P*Ch*K -1, 2, & 3.

Data Classification

Table 2 Two ways to classify from factor analysis results. Based on a semantic differentiation scale from 1: 'very poor or never occurred' to 5: as 'very good or occurred very often'.

CLASS A: P*Ch*K oriented			CLASS B: Function oriented		
Instrument	Mentor &	Requires Chem Knowledge	Instrument	Chemical Manager &	Chemical Concept Teacher
UGs'	4.59	4.11	UGs'	4.29	4.21
Instructors'	4.67	3.44	Instructors'	4.34	3.22

We found two useful ways to classify these constructs from Table 1. In Table 2 we described them as Class A and Class B. Our discussion of pedagogical chemical knowledge will involve only Class A. (Class B was used with GTAs to emphasize their functions as procedural manager and chemistry teacher. Table 3 provides a summary of each section of Table 1 classified into four forms of P*Ch*K.

Table 3 Summaries of Forms of Pedagogical *Chemical* Knowledge (PChK)

Form PChK	Table 1	Part of GTA Function	Knowledge Requirement	Examples
PChK-0	I-D	Management of the Laboratory Environment	Mentoring that does *not* require chemical knowledge.	Interacts with students; Helpfulness; Respects students' abilities to learn
PChK-1	1-C	Management of Chemical Laboratory Environment	General procedural knowledge of chemical lab work; Specific technique, procedures, calculations, and safety knowledge of each lab investigation	Models and enforces safety precautions; Demonstrates techniques; Troubleshoots lab problems; Gives guidance to students
PChK-2	1-B	Teaching Chemical Concepts	Understanding chemical topics and concepts in order to transform them to make sense to students (which is dependent on student knowledge)	Correlates macro-level events with nano-level processes; Chooses examples wisely; Links chemical symbols, math variables, and nano-level processes together
PChK-3	1-A	Teaching Chemical Concepts	Flexible knowledge to probe and guide student's reasoning as well as confidence in knowledge and role so as to direct the learning environment	Uses questioning strategies to probe conceptual reasoning; Gives occasional directed guidance; also directs students to work through questions or procedural problems with each other

Discussion of Results Associated with Research and Practice

There is a need for a theoretical basis of pedagogical content knowledge, particularly in the work of transforming chemical knowledge (Bucat, 2004). Perhaps these definitions of a variety of forms of P*Ch*K will provide that theoretical basis. Table 3 gives a short overview on the forms of P*Ch*K that we determined in chemistry lab. Therefore, we call this knowledge and performance pedagogical chemical knowledge, P*Ch*K.

Analyzing Pedagogical Content Knowledge

Difficulty in demonstrating the chemical knowledge and pedagogical sophistication of the forms of P*Ch*K was judged by the frequency of performance. The aspects of P*Ch*K-3 performance were seen the least often, and P*Ch*K-1 interactions were observed most often. The amount of chemical understanding and pedagogical sophistication required of the GTA for effective interactions increases from interactions showing P*Ch*K-1 to those showing P*Ch*K-3. High P*Ch*K-2 performers worked to attain sensitivity to student knowledge because it permitted their explanations to work better with their UGs. To perform with P*Ch*K-3, knowledge must be well organized and flexibly applicable to guide students' work effectively and facilitate UGs in mechanical reasoning with components of the experiment and facilitate conceptual reasoning with the underlying concepts that the lab illustrates. Helping students to reason requires the knowledge base of P*Ch*K-2 as well as that of P*Ch*K-3. Further, interactions of P*Ch*K-3 require that GTAs take control of the learning environment in a professional manner. Final results clearly showed that the GTA instructors needed to put more developmental emphases on P*Ch*K-2 and P*Ch*K-3 interactions so that GTAs would meet the instructors' higher standard of chemistry teaching.

PChK-0

Any knowledge possessed and acted upon by the chemistry GTAs that did not require chemical knowledge was labeled P*Ch*K-0. These are the interactions we described as responsive mentoring, which are important pedagogical actions. The UGs gave GTAs high marks for P*Ch*K-0. This is not surprising since new teachers often believe that their primary role is to have cooperative and friendly relationships with students (Geddis, 1993).

PChK-1

The P*Ch*K-1 performers required understanding of chemistry at the lab level to give general procedural guidance and give directed advice. See Table 3 for specific interactions. GTAs demonstrated techniques and provided relevant, helpful advice on the work progress during the lab session. The interactions of P*Ch*K-1 correspond most closely to the UG's procedural emphases in that UGs wish to get the lab experiment started quickly and finished quickly (Malina and Nakhleh, 2003). Much of the knowledge employed in P*Ch*K-1 may have been generated from the GTA's own UG lab experiences because the teaching model in those labs was more likely to have been one primarily of transmitting procedural knowledge (Abraham et al., 1997, Hilosky et al., 1998). Thus, modeling of P*Ch*K-1 on past laboratory educational experiences when they were UGs may account for the ease of GTAs' understanding and the frequency of exercising P*Ch*K-1 interactions. Evidence supporting this claim is that international GTAs, who often have strong theoretical knowledge but less UG laboratory experience (Tanner et al., 1993), have more difficulty acquiring P*Ch*K-1 than domestic GTAs (Bond-Robinson and Rodriques, In press). The UGs' and instructors' ratings indicated that the most complicated and difficult aspect of P*Ch*K-1 to execute effectively was preparation and delivery of an appropriate talk. These were far more challenging to learn that it was for GTAs to provide guidance or give specific pertinent advice as the lab proceeded.

PChK-2

Performance showing P*Ch*K-2 required groundwork ahead of time, which is an essential aspect of transforming subject matter into forms for student consumption. As they prepared for lab, GTAs had to *identify* underlying abstract chemical concepts that related to the lab investigations if they were to be effective in helping students understand abstract concepts that underlie the lab investigation. The following GTA difficulties emerged during seminar discussions and videotaped teaching observations. The value of identifying concepts was not evident to most GTAs at first; some never understood the need to identify them because they were not mentioned in the lab procedure. Facilitating UGs to connect these underlying abstract concepts with their lab work required that GTAs make some decisions ahead of time about ways to transform subject matters, e.g., by identifying clear examples; relating the reality of the laboratory to the atomic/molecular level; devising analogies from a familiar idea to a chemical one; or putting together mathematical variables to explain chemical processes. Even if the GTA identified the abstract concepts, it was very challenging to produce explanations at the level of UGs' knowledge. GTAs had to figure out the extent of their UGs' knowledge and abilities to reason, and doing so demanded some tactics. Transforming chemical knowledge was difficult for all and totally neglected by some GTAs. In summary, many actions indicating P*Ch*K-2, e.g., linking the lab to the abstract concepts of lecture, and making effective explanations at the level of UGs that were more than restatements of the chemical view, were weakly executed or non-existent after one semester. The weak performance here is one reason that instructors rated GTAs as barely above mediocre in chemistry teaching (See Table 2.).

PChK-3

The P*Ch*K-3 interactions performed by a GTA promoted reasoning between the GTA and UG(s) or among UGs. The P*Ch*K-3 required more aggressive objectives and positioning as well as the ability for a GTA to flexibly exploit his or her chemical knowledge as needed. The challenge GTAs found in understanding and executing P*Ch*K-3 was the other reason for their mediocrity in chemistry teaching. Some GTAs were uncomfortable 'butting into' the UGs' workspaces. Many GTAs responded with inertia when the situation called for beneficial prompting of reasoning by using generic and directed questioning strategies (Davis, 2003). A generic question is not focused on a specific answer; instead its purpose is to encourage students to think and articulate, e.g., "*Tell me about what you just finished*." Use of directed questions that asked about specific concepts was a more familiar technique, but GTAs generally performed directed questioning in only limited fashions. When a GTA did attempt to guide a group's thinking in a troubleshooting process, doing so utilized the GTA's own mechanical knowledge and confidence. Some GTAs never encouraged a group of UGs to discuss a problem or question among themselves. Our data showed that the interactions involved in P*Ch*K-3 were more difficult for new GTAs to perform than those of P*Ch*K-2.

Implications For Teaching and Learning

One of the ways to clarify scientific explanations is to be as precise as possible about what they are. In the literature of science education, scientific explanations are discussed under many different banners: as theories, as models, as argument patterns, as analogies, as mathematical equations, as exemplars. As far as the classification hierarchy goes, 'explanation' is the generic, overarching term. Descriptors, such as theories, models, analogies, etc., interact as sub-categories under the category of explanation.

What does it mean to transform chemical subject matter?

I have used the term, transformation, as others do (e.g., Bucat, 2004), because it is a part of Shulman's description of what PCK looks like. Shulman describes the kind of explanations that effective teachers make as transformations of subject matter knowledge, which are appropriate to the level and specific characteristics of their student populations. This kind of explanation is named, a *transforming explanation*, in that this kind of explanation makes the representational meaning explicit that chemists have for chemical ideas by connecting them to the macroscopic level of the students. Since transforming explanations are appropriate to the level and specific characteristics of their student populations, it is important to know how students think about scientific explanations. A great number of studies in science education have examined the relationship of students' explanations of various scientific phenomena with those of scientists, but none have examined UGs' views of what a scientific explanation actually is. I did a study with an undergraduate researcher to examine general chemistry students' views of scientific explanations (Bond-Robinson, 2004, Bond-Robinson and Harrington, 2004). We found that students' responses indicated they had actually answered two different questions: (1) aspects of science-course topics they thought needed to have an explanation, and (2) characteristics that make an explanation effective for them personally. They wanted explanations about facts of the discipline as they were related to natural phenomena; procedural knowledge such as how, when, or what to do in assignments or problem solving; and applications to their own lives from topics under study. Further, students expected clear explanations of *what they needed to know*. Characteristics of good explanations were closely linked to their current knowledge and relevant to them personally. Good explanations were simple as opposed to complex or technical; good explanations were concrete as opposed to abstract. We found their expectations about the nature of scientific explanations in a science course to be pragmatic, personal, daunting for teachers to meet, and fairly unrelated to the theories in science. The study of science produces explanations, which tend to be theoretical in modern science; these explanations are not concrete, simple, or necessarily at the level of any student since scientific explanations are generated by scientists for other scientists. Commonly, teachers believe that their job is to show students how scientists have explained particular phenomena. Unless the scientific explanation is fairly radically transformed, the students will not recognize the statement as an explanation for them. For example teachers expect to explain the theories and models of their science, which are representational explanatory tools for scientists. Students did not find it necessary to reason like a chemist to gain effective chemical explanations. A specific definition for transforming explanations could be the aspects of chemistry that are not obvious to students, aspects of chemical reasoning that require a teacher to demonstrate and for which students need help to utilize. *A transforming explanation is a chemistry-specific illustration of how chemists think about a chemical process, which is linked by the explanation to students' thinking of that same chemical process.* In chemistry students' thinking, the process is likely to be at a macroscopic level of their personal experience with objects or events associated with a chemical process, supplemented by textbook and class-taught ideas, facts, and pictures. Students may not accurately distinguish between a chemical process and a conceptual object. We will discuss the student's failure to distinguish between them later.

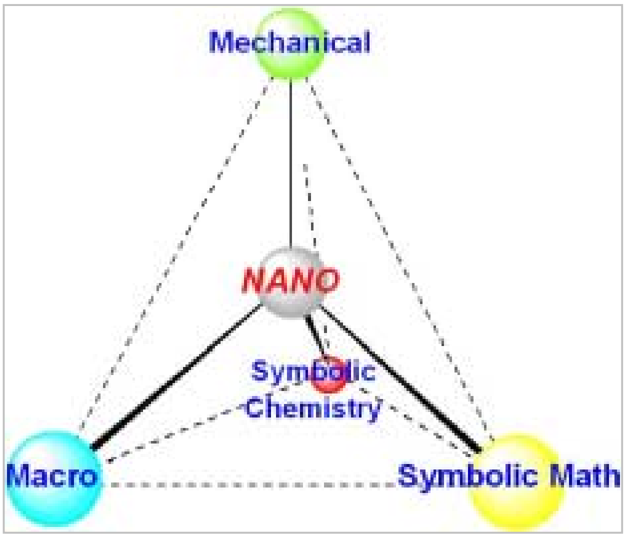
Chemical Explanations and 'Transforming Explanations' of Chemistry for Students

What explanations does the science of chemistry provide? What are these representational tools? In chemistry chemists discuss the occurrences of chemical reactions using atomic and kinetic theories and those of thermochemistry. Chemists explain why and how those reactions occur with accompanying stoichiometry at the invisible level of atoms, ions, and molecules. Understanding the chemical meaning of a reaction is to correlate the visible chemical change with a mental model of atoms, ions, and molecules reacting in a nanoscopic world. Further, chemists see a process occurring over time rather than a static conclusion.

The chemical explanations must be transformed to the level of the student population, which will be a 'transforming explanation.' Note that understanding stoichiometry requires that students acquire a mental model of a process in motion, visible chemical change, and connections to the nanoscopic world of atomic and molecular interactions. Transforming explanations have the power to guide students in developing an appropriate mental model. Students of chemistry must learn to express this chemical process symbolically in an appropriate chemical sentence, keeping track of correct chemical formulas and conservation of mass. Finally, they must apply proportional reasoning so they can utilize mathematical symbolism to calculate the magnitude of reactants required to form a designated magnitude of one of the products.

Figure 1 shows a tetrahedral model of chemical reasoning, which deals with the ramifications of the stoichiometry example and reflects how chemists routinely move among representations of each modality as they solve problems. The tetrahedron is an adaptation of Johnstone's two-dimensional triangular model (1991) that shows sub-microscopic, symbolic, and macroscopic representations of chemistry at each corner. Bucat (2004) emphasized that the meaning of chemical representations has to be acquired by students new to the field of chemistry. Teachers must teach the representations that chemists use in their work, which are highly varied even when related to the same process (as shown in the stoichiometry example). Some nanoscopic representations are formulas for compounds as well as structural 2-D and 3-D structural representations.

Figure 1 Five Modes of Representational Reasoning in Chemical Work



Chemists use the term, mechanism, to describe the step-by-step process in which atoms, molecules, ions and electrons interact to complete a reaction at the nanoscopic level. A reaction can be viewed as a system of working parts (Agnes, 1999), which brings to mind the substrates, equipment, reagents, and methods that led to the reaction mixture. As a result, mechanistic systems exist at both the nanoscopic and macroscopic levels of interaction. It may be that students do not expect to learn, or do not realize that they need to learn, explanations that have layers of complexity. Therefore, part of the difficulty in learning chemistry may be that students do not realize that explanation in chemistry requires using the multiple ways in which chemists reason about a chemical process.

Transforming explanations have the capacity to illustrate the true nature of chemistry. Since students' experiences exist at the macroscopic level, effective transforming explanations must repeatedly come back to the macro level of the chemical process under study. In the past we have called this kind of transforming explanation, 'making chemistry relevant to students'. The tetrahedral model of representational reasoning allows chemists to become more systematic when designing transforming explanations for their students. When making a transforming explanation teachers must start from what students already know and find ways to reasonably connect them to another chemical representation of that process under study. Thus, transforming explanations occur one at a time.

How to Transform Chemical Knowledge (PChK-2)

The nature of transforming explanations clearly depends directly on the disciplinary content as is illustrated with chemistry. In chemistry, the specific definition of transformation of chemical subject matter knowledge utilizes the representational reasoning of chemists. The analogies, theories, exemplars, models and mathematical equations will all be closely related to the same representational reasoning patterns that were illustrated in the tetrahedral model.

Our grounded definition of P*Ch*K-2 requires that teachers link the concrete environment of the lab with abstract concepts and representations of concepts occurring in chemical processes. We hypothesize from Figure 1 that transforming explanations in chemistry require linking macroscopic matter and events to nanoscopic particles and processes and their corresponding chemical symbolic representations. Some transforming explanations additionally require mathematical symbolism in equations. All these transforming explanations are examples of reasoning. Thus, Figure 1 with its five modes of representational reasoning illustrates that teachers can make explicit explanations in a variety of ways. For example, chemical explanations of phenomena are usually given at the nanoscopic level in the textbook. Using Figure 1 as a template, the teacher can transform the nanoscopic explanation in at least four ways: (1) remind students of the relevant objects and materials that are present in the environment; (2) illustrate the macro mechanical system pictorially as it happened or will happen; (3) write the chemical symbols that represent everything that occurred in the chemical process; and (4) introduce the mathematical relationship among variables that shows the cause and effect relationships, and which quantifies the chemical process. Crucial in transforming explanations is that students' attention is directed to specific features of each type of chemical representation. Many teachers readily illustrate some of these representational differences and how chemists use them. The difference in what I am proposing is that using the tetrahedral model about how chemists reason leads to *systematic* generation of transforming explanations each time we teach a new topic.

Graduate students have knowledge about chemical topics, but the vast majority does not have knowledge about what Bucat (2004) calls "*particular teaching and learning demands*" (p. 217). New teachers must learn to transform subject matter to produce effective explanations. In Table 4 we utilize the tetrahedral model of representational reasoning and describe the teaching demands of a common lab topic that many of our GTAs taught recently, the enthalpy of phase changes. We show how the teaching/learning demands relate to differing representations integral to these five modes of reasoning. In an experiment investigating enthalpy of phase changes, the UGs would benefit from transforming the mechanics of the calorimetry system to specific relationships among matter and energy. For example, a reasonable connection exists between the ΔT in an equation about heat of phase change and the perceived change in temperature of water in their calorimeters, which is sensed or seen instrumentally as a moving line on a real time graph. The amount of temperature change can be related to a conceived concept that chemists use to describe how different materials transfer heat differently, *specific heat capacity*. Another transforming explanation connects the change of temperature to the change in kinetic energy of moving water molecules and molecular motion in phase changes. Reasoning about the kinetic energy leads readily into reasoning specifically about intact molecules (using structural formulas) to avoid the conception that change of phase involves breaking of *intra*molecular bonds. Individual transforming explanations, such as these *made over time* by an instructor, enable students to learn how to reason at the unseen nanoscopic level where most chemical explanations of phenomena transpire.

Why must teachers promote chemical reasoning by their students using PChK-3?

Teaching science as static facts, static representations, or static models requires no reasoning. Producing explanations that make chemistry understandable to students requires that the teacher show them how to reason like a chemist. Chemists reason with the varied forms of representations chemists use. Teaching students the representations of chemistry is getting students to 'see' things in motion the way that chemists do. Reasoning with chemical representations includes specially designed words that represent scientific concepts created as tools to conceive (Blumer, 1931). For example atoms, electricity, and mass are such conceptions, which we could call *theoretical objects*. Theoretical objects are components of chemical models. The complexity and special definitions for students to understand are challenging. Without conceptual understanding many students do not distinguish between similar theoretical concepts, such as between heat and temperature (Carson and Watson, 1999; Harrison et al., 1999; Greenbowe and Meltzer, 2003). Clearly, students can benefit from transforming explanations that show how verbal, theoretical vocabulary is connected to concrete instances in the lab, i.e., a transforming explanation from explanatory theoretical relationships to relationships among concrete objects and visible processes.

Mechanical reasoning in the tetrahedral model is our addition to a portrayal of chemical thinking. Chemical thoughts are not static facts or representations. Chemical thinking describes chemical processes or mechanical systems that chemists build. It has been pointed out in the cognitive literature (Chi, 1992) that matter and processes are often confused in students' natural classifications of chemical phenomena. Producing a transforming explanation requires teachers to help students separate chemical processes from chemical objects, for example distinguishing between the chemical conception of movement of energy and the conception of a material quantity of heat (such as 19th century caloric theory). Mechanical reasoning describes a sequence of cause and effect relationships. Models are one type of mechanical explanation. General classroom usage of the term, model, may also be confused between an object and a process. The word model implies a representation that is a standard of excellence, or a small copy of an existing object such as model car; additionally a model is also defined as a guide or plan to be followed, (Agnes, 1999) such as a blueprint. The latter of these connotations fits the scientific usage of models best whereas the model car is probably the more common connotation of model for students. The solar system model of the atom is not important for how the atom looks; it is important for what it reveals about how an atom works. The chemist visualizes an atomic model as a *working* model. I argue that a scientific model illustrates how theoretical objects work; a scientific model is not a static representation. Therefore, teaching students the representations of chemistry is getting students to 'see' things in motion the way that chemists do. Teaching science as static facts or static models requires little in the way of reasoning. Therefore, transforming explanations made to students in chemistry often involve mechanical reasoning of a sequence of cause and effect relationships in chemical processes with theoretical objects or in a mechanical system built with macroscopic objects.

How to Promote Reasoning Among Chemistry Students (PChK-3)

Modeling reasoning by making transforming explanations to students at their levels of understanding is the first step toward getting students to reason by making transforming explanations themselves. Thus P*Ch*K-2 precedes P*Ch*K-3. The tetrahedral model can be used as an instrument for teachers to reason among chemical representations with their students; but the teacher has to be modeling this kind of reasoning explicitly in order for students to acquire the pattern and the habit. Following exemplary modeling the tetrahedral figure as a tool is at least as significant for students to use similarly and explicitly. The action and thinking required to write out each type of representational usage, to draw the representations of each type, and to reason through each of them allow students to visualize the similarity of meaning among representations and gradually acquire understanding of the uniqueness of meaning shown by the features of certain representations. Bucat (2004) worries about limiting complex understandings when he describes "*statements subject to shallow interpretation*" (pp. 217-218) that lead to the superficial understandings of chemical phenomena. Visualizing multiple modes of representations and reasoning from one to another requires that students perform *chemical* reasoning, which leads them into deeper understanding from a chemical point of view. Ideally, learning to make a transforming explanation one at a time, i.e., from one mode of representation to another, avoids overloading functional working memory.

Generalizability of P*Ch*K to Science Labs and Inquiry

Although this study investigated lab teaching by graduate students in general chemistry and organic chemistry, the three forms of PChK have broader applicability to PCK in the sciences. For example, the progression of knowledge building and performance that revealed itself among graduate students in chemistry is relevant to teaching assistants in other science laboratories. The instructors' and UGs' instruments would fit any science lab setting. Secondly, 'transforming explanation,' defined as a discipline-specific illustration of how people in that discipline think about a disciplinary process, which is linked by the explanation to students' thinking about that same disciplinary-related process, is generalizable as written to all forms of PCK.

The development of graduate students parallels many aspects of novice classroom teachers' development as they teach students in secondary and primary schools. Strategic interactions were adapted from constructivist teaching inventories used at the secondary level that were *not* chemistry specific. These twelve interactions are ideal ways to facilitate and assess the quality and frequency of these interactions in the classroom as teachers attempt to implement and facilitate student inquiry activities.

Results and implications from this work can apply directly and beneficially to pre-service science teachers under the conditions that a progression of development is encouraged. Currently, there is little emphasis on teaching prospective teachers about the day-to-day mechanisms to facilitate disciplinary knowledge construction by students. Emphases on questioning strategies, (e.g., Davis, 2003; Penick, 1996), have been useful, but they are not usually seen in a constellation of twelve interactions between the teacher and students. In addition, this study showed that a natural progression exists from the mentoring practices of P*Ch*K-0 to the procedural knowledge of P*Ch*K-1. It is a greater challenge for teachers to transform their own subject matter knowledge on the relevant science topics (PCK-2). Finally, it is a further significant transition to learning how to orchestrate and promote students' to reason in a disciplinary fashion, which is a manifestation of PCK-3.

Missing Forms of PChK Not Found in the Laboratory

The laboratory-teaching assistants do *not* design the laboratory program; faculty members and laboratory coordinators do. Thus, a significant portion of teacher expertise is absent in laboratory teaching. Therefore, we propose the identity of P*Ch*K-4 that supplies that missing expertise in a chemistry classroom. Generic PCK-4 is demonstrated when teachers design effective day-to-day curriculum, activities and resources for their population of students. This labeling of practical, useful, and strategic design knowledge as PCK-4 is appropriate, not because it is the last identified, but because the demonstrated work of PCK-4 requires the knowledge of procedural work at the macro level, transforming explanations of topics in effective explanations in many reasoning modes, and direction of an effective learning environment that promotes reasoning among students, thus PCK-1 through PCK-3. Therefore, laboratory teaching is an appropriate *prerequisite situation* for new teachers to experience the responsibilities for student learning. They begin teaching practice by acquiring PCK-1, PCK-2, and PCK–3 before the necessity arises to learn how to design day-to-day disciplinary curriculum and activities. We hypothesize that a PCK-5 construct could exist that represents the craft knowledge necessary to prepare pre-service and in-service science teachers for directing and facilitating deeper science learning among their students which require PCK-0 to PCK-4.

Conclusions

The difficulty in acquisition of forms of P*Ch*K occurs in the order: of P*Ch*K-3 >P*Ch*K-2 > P*Ch*K-1 > P*Ch*K-0. The interactions of P*Ch*K-1 overwhelmingly occur at the level of the macroscopic environment. The P*Ch*K-1 interactions involve generally operating at the tangible, observable level of concrete objects. Table 4 gives macroscopic examples of reasoning that occurred in a lab experiment about enthalpy of phase changes. In addition to macroscopic sensing and availability of tangible objects, macro-mechanical reasoning illustrates procedures carried out by UGs. The obvious macroscopic nature of P*Ch*K-1 interactions is another reason that GTAs perform them at a higher frequency than interactions of P*Ch*K-2 and P*Ch*K–3. The obvious nature of P*Ch*K-1 interactions also explains why the UG labs that GTAs experienced were likely to have modeled procedural macroscopic types of interactions between teacher and students. Therefore, the new teachers' difficulties in performing with P*Ch*K-2 and P*Ch*K-3 are due to at least two factors: infrequent modeling of constructivist teaching practices experienced as students, and the nature of chemistry's explanations of phenomena that describe theoretical objects (scientifically conceived concepts) interacting through conceptualized processes at the nanoscopic level.

Table 4 Modes of chemical reasoning in a laboratory experiment: enthalpy of phase changes

MODE OF REASONING	EXAMPLES
NANO REPRESENTATION	Molecules and their activities, changes in kinetic energy of molecules, changes in intermolecular forces among molecules; latent heat energy used to change intermolecular forces instead of changing temperature. These are examples of theoretical objects.
MACRO REPRESENTATION	Finding and touching equipment Seeing melting, vaporizing, and subliming Physically sensing temperature and its changes Graphically seeing temperature change as generated by probe & software Words and pictures from reading about the lab experiment Seeing and hearing directions and pictures on chalk board
MECHANICAL REPRESENTATION	Mechanical Work at Macro Level: Make a calorimetry system to generate desired data Measuring the mass of a substance Combining two substances at different temperatures Mechanical processes at Nano Level: Physical process of phase changes at the level of moving molecules Mechanical processes expressed at Mathematical Level: Relationship of change in temperature to the heat capacity of a particular substance Relationship of heat gain to enthalpy Relationship of Law of Conservation of Energy to their experiment
CHEMICAL REPRESENTATION	$N_{2\,(l)}$ $CO_{2\,(s)}$ $H_2O_{(s)}$
MATHEMATICAL REPRESENTATION	ΔH, s, ΔT, q; $q = m\,s\,\Delta T$

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Appendix

Additional Information about the Instruments' Content and Operational Definitions

The *content* of the instruments contained strategic interactions necessary for a high-performing laboratory learning environment. The content of the instruments came from several sources. One source was the educational reform literature (Ausubel, 1968, Bruner, 1966, Dewey, 1916, Novak and Gowin, 1984). Another source was a valid constructivist observation instrument, the ESTEEM model, used in science classes (Burry-Stock and Oxford, 1994; Enger and Yager, 1998; Yager and Weld, 1999; Burry-Stock et al., 2000) that had been used by the author. The original ESTEEM instrument was not evaluated for the format, tasks, and time period in a chemistry laboratory setting; therefore, items relevant for teaching in the chemistry laboratory were added, e.g., enforcing safety, giving an opening talk, and specific procedural guidance in the laboratory. The first instrument for the instructors to use contained twenty-seven items as a result of the three content influences of the reform literature, the ESTEEM instrument, and the items specific for the chemistry laboratory. The items on the instrument are considered strategic interactions that, when executed well, lead to an effective laboratory learning environment for students. Thus, the purpose of designing this instrument was to pinpoint the strategic interactions, which then become the criteria for measuring a GTA's teaching performance. The quality scale runs from very poor (rating of 1) to very good (rating of 5). Alternatively, a frequency scale ran from 'never' to 'very often'. Content and construct validities were independently established over four iterations of the course. Validity of the instrument contents was thus based on the literature about characteristics of a constructivist-learning environment and the content of practical work done in a laboratory setting.

Construct validity was evaluated in the new setting with the population of students who enroll in laboratories as well as the very small group of two instructors who assessed GTA performance. First, *construct* validity depended upon consistent measurability of definitions that were created to describe each interaction. If an *operational definition* did not encourage clear measurement, the definition for that interaction was changed or dropped, thus increasing the overall construct validity of the instrument. Over four iterations of the course operational definitions were modified, replaced with ones that could be recognized and measured more consistently, or dropped entirely. The original twenty-seven interactions were honed to the current set of twelve that could be reliably measured. See the first column of Table A-1 for the twelve interactions. Constructs are also referred to as variables.

The Instrument Survey Given to Undergraduate Students in the Laboratory

Data derived from the UGs' instrument below was used as the basis for the factor analysis performed to determine the forms of P*Ch*K.

Table A-1 Undergraduate Students' Instrument: Operational definitions in relation to the twelve strategic interactions

Strategic Inter-action	UGs' Instru-ment #	CONSTRUCT (variable) interaction	OPERATIONAL DEFINITION
4	1	Directions	My TA's short talks are helpful to my understanding.
2	2	Safety	My TA models safety and other lab rules and enforces them.
1	3	Interaction	My TA interacts with me throughout the lab.
3	4	Helpful	My TA helps me when I ask for help.
3	5	Respect 1	My TA is respectful of me as a person.
3	6	Respect 2	My TA is respectful of my knowledge and ability to learn.
12	7	Trouble 1	My TA encourages us to discuss our procedural problems together as a team.
12	8	Trouble 2	My TA encourages us to think through problems or mistakes rather than telling us what to do or doing it for us.
6	9	Guidance	My TA's comments on troubleshooting are relevant and at the level of my knowledge.
5	10	Awareness	My TA helps me when I am having difficulty with the experiment, even if I do not ask.
7	11	Advice	My TA's comments are helpful to my work as the lab progresses.
8	12	Links Concepts	My TA links underlying chemical concepts from the lecture to the lab experiment to help me understand how they connect.
10	13	Prompts Ss	My TA prompts me about underlying concepts of the experiment when I ask questions.
9	14	Explanations	My TA explains the chemical concepts underlying the experiment with me.
11	15	Discussions	My TA stimulates us to discuss the concepts underlying the experiment with each other.