

# An expanded framework for analyzing general chemistry exams

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Received 19th October 2009, Accepted 24th April 2010

DOI: 10.1039/C005463C

This paper describes an expanded framework to aid chemical educators in constructing exams for their courses. The framework has three primary levels: definition, algorithmic, and conceptual. These primary levels have often been used in chemical education research to analyze and describe exam questions, but in this study the definition, algorithmic, and conceptual primary levels have expanded secondary levels.

**Keywords:** chemical education research; General Chemistry; testing/assessment

## Introduction

Most people involved with chemistry would agree that the teaching, learning, and assessment of chemistry involve both algorithmic and conceptual components. Many educators might experience difficulty in determining the proportions of algorithmic and conceptual components on their exams. The framework presented here examines this issue.

Zoller *et al.* (1995) define algorithmic questions as: “questions that require the use of a memorized set of procedures for their solutions” and conceptual questions as: “questions that may be text-based or diagrammatic and require students to invoke underlying concepts of the basic theories of science in order to answer the question.” Some authors (Pickering, 1990; Mason *et al.*, 1997) contend that instructors favor either an algorithmic or conceptual approach when teaching chemistry. Others (Pushkin, 1998) place chemistry students on a cognitive development spectrum, with conceptual learners appearing at the more evolved end of this spectrum, and algorithmic learners, presumably, appearing at the less evolved end of this spectrum.

Regardless of how algorithmic and conceptual components are manifested in the chemistry classroom, research has shown that in exams many students who achieve success on algorithmic questions do not achieve comparable success on conceptual questions (Nurrenbern and Pickering, 1987; Sawrey, 1990; Niaz and Robinson, 1992; Bunce, 1993; Nakhleh, 1993). These results indicate that many students are able to successfully apply algorithms even in the absence of meaningful conceptual understanding.

The algorithmic or conceptual chemistry questions test different kinds of learning. For example, Novak and Gowin (1984) adapted Ausubel’s theory on learning, and they considered learning to be on a continuum, with rote learning at one end and meaningful learning at the other. Rote learning involves verbatim memorization without connecting new

knowledge to existing understanding, whereas meaningful learning involves the interaction of new knowledge with current understanding. In this framework algorithmic learning would fall between rote and meaningful learning, and conceptual learning would fall closer to the meaningful end of the learning continuum. Indeed, Bodner (1991) has indicated that the process of learning sometimes results in the construction of algorithms, such as those used in answering questions on stoichiometry. These algorithms are then used to provide solutions to similar types of questions. It is important for chemical educators to note these differences in the kinds of learning and in the performances of students on various types of chemistry questions. There are several important educational implications that arise. In particular, recommendations have been made to shift chemistry instruction from an algorithmic orientation to a more conceptual orientation (Zoller *et al.*, 2002). Therefore, a mechanism which could provide detailed characterizations of chemistry questions would be helpful.

Several suggestions have been made to expand the categorization of chemistry questions beyond algorithmic or conceptual. Zoller *et al.* (1995) recognized four types of chemistry questions: algorithmic, conceptual, lower-order cognitive skills (LOCS) and higher-order cognitive skills (HOCS); much work has been carried out to investigate these categories (Zoller, 1993, 1996, 2000; Zoller and Tsapalis, 1997; Zoller *et al.*, 1999; Tsapalis and Zoller, 2003; Zoller and Pushkin, 2007). Robinson and Nurrenbern (n.d.a) described three broad categories of chemistry questions: recall, algorithmic and higher-order. Stamovlasis *et al.* (2004, 2005) categorized four types of chemistry questions: knowledge-recall, simple algorithmic, demanding algorithmic and conceptual. Dori and Hameiri (2003) took another approach and analyzed quantitative stoichiometry questions in terms of bidirectional transformations between masses and chemical symbols, chemical symbols and particles, and finally, chemical symbols and chemical equations. Wolfskill and Hanson (2001) have developed a software product they call LUCID, which stands for Learning and Understanding through Computer-based Interactive Discovery. Quizzes are one feature of LUCID, and the performances of students on these quizzes were resolved at the levels of information, algorithmic application, conceptual understanding, and

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**Table 1** Correspondence of literature categorizations of chemistry questions with relevant knowledge and cognitive process dimensions

Cognitive process dimension	Knowledge dimension				
	Remember	Apply	Analyze	Evaluate	Create
Factual knowledge	LOCS <sup>2</sup> , recall <sup>3</sup> , knowledge-recall <sup>4</sup> , information	LOCS <sup>2</sup> , knowledge-recall <sup>4</sup>			
Conceptual knowledge		Conceptual <sup>2,4</sup> , HOCS <sup>2</sup> , higher order <sup>3</sup> , problem solving <sup>6</sup> , conceptual understanding <sup>6</sup>			
Procedural knowledge		Algorithmic <sup>2,3</sup> , LOCS <sup>2</sup> , HOCS <sup>2</sup> , higher order <sup>3</sup> , simple algorithmic <sup>4</sup> , stoichiometric transformations <sup>5</sup> , algorithmic application <sup>6</sup> , problem solving <sup>6</sup>	HOCS <sup>2</sup> , higher order <sup>3</sup> , demanding algorithmic <sup>4</sup> , problem solving <sup>6</sup>		

<sup>1</sup>Anderson and Krathwohl, 2001; <sup>2</sup>Zoller *et al.*, 1995; <sup>3</sup>Robinson and Nurrenbern, n.d.a; <sup>4</sup>Stamovlasis *et al.*, 2004; <sup>5</sup>Dori and Hameiri, 2003; <sup>6</sup>Hanson and Wolfskill, n.d.a.

problem solving, as adapted from Bloom's taxonomy (Hanson and Wolfskill, n.d.a).

A revised version of Bloom's taxonomy (Anderson and Krathwohl, 2001) presents learning outcomes categorized hierarchically along two interacting dimensions, the knowledge dimension and the cognitive process dimension. The knowledge dimension contains the hierarchical categories of factual knowledge, conceptual knowledge, procedural knowledge and meta-cognitive knowledge. The cognitive process dimension contains the hierarchical categories of remember, understand, apply, analyze, evaluate, and create. Anderson's and Krathwohl's revision (2001) of Bloom's taxonomy provides a useful framework for organizing the chemical education literature reviewed above. For example, within the knowledge dimension, the factual knowledge category corresponds to part of the LOCS category of Zoller *et al.* (1995), the recall category of Robinson and Nurrenbern (n.d.a), the knowledge-recall category of Stamovlasis *et al.* (2004), and the information category of Hanson and Wolfskill (n.d.a). The conceptual knowledge category corresponds to the conceptual and part of the HOCS category of Zoller *et al.* (1995), part of the higher order category of Robinson and Nurrenbern (n.d.a), the conceptual category of Stamovlasis *et al.* (2004), and the conceptual understanding and part of the problem solving category of Hanson and Wolfskill (n.d.a). The procedural knowledge category corresponds to the algorithmic and parts of the LOCS and HOCS categories of Zoller *et al.* (1995), the simple algorithmic and demanding algorithmic categories of Stamovlasis *et al.* (2004), the stoichiometric transformations of Dori and Hameiri (2003), the algorithmic and part of the higher order category of Robinson and Nurrenbern (n.d.a), and the algorithmic application and part of the problem solving category of Hanson and Wolfskill (n.d.a).

Within the cognitive skills dimension of the revised Bloom's taxonomy, for example, the 'remember' category corresponds to the processes of part of the LOCS category of Zoller *et al.* (1995), the recall category of Robinson and Nurrenbern (n.d.a), the 'knowledge-recall' category of Stamovlasis *et al.* (2004), and the 'information' category of Hanson and Wolfskill (n.d.a). The 'apply' category corresponds to the processes of the algorithmic, conceptual, HOCS, and part of the LOCS category of Zoller *et al.* (1995),

the stoichiometric transformations of Dori and Hameiri (2003), the algorithmic and part of the higher order category of Robinson and Nurrenbern (n.d.a), the simple algorithmic and conceptual categories of Stamovlasis *et al.* (2004), and the algorithmic application, conceptual understanding, and part of the problem solving category of Hanson and Wolfskill (n.d.a). The 'analyze, evaluate, and create' categories correspond to the processes of the conceptual and HOCS categories of Zoller *et al.* (1995), the higher order category of Robinson and Nurrenbern (n.d.a), the demanding algorithmic and conceptual categories of Stamovlasis *et al.* (2004), and the conceptual understanding and problem solving categories of Hanson and Wolfskill (n.d.a). These correspondences are summarized in Table 1. In addition, for the remainder of this article, we will continue to discuss knowledge and cognitive processes in terms of recall, algorithmic, and conceptual, which reflects the traditions of our discipline.

We argue that chemical educators would benefit from a framework that could be used to characterize any general chemistry question on a reasonably detailed level. We define a reasonably detailed level to mean that the characterization of a question should indicate the kind of data presented to the student in the question (text, numbers, diagrams), as well as indicate the kind of thinking the student will likely employ to answer the question. A suitable framework would ideally cover the range of categories defined by Zoller *et al.* (1995) and Robinson and Nurrenbern (n.d.a), and it would cover them to the level of detail of the stoichiometric question components proposed by Dori and Hameiri (2003). This type of framework could be useful to chemical educators in analyzing the frequencies of these different types of questions on general chemistry exams, and in constructing and editing their exams.

Our research question was as follows: What is the nature of a framework that could be used to analyze any general chemistry question on a reasonably detailed level?

## Methods

We chose to develop a framework for general chemistry questions based on pre-existing general chemistry exams. We used the American Chemical Society First Term General Chemistry Special Examination, as well as the Second Term

General Chemistry Special Examination (American Chemical Society, 2009), because these exams served as one component of a new graduate program at Youngstown State University (Bretz, 2002), which we were evaluating. These examinations were prepared in 1997 in collaboration with the 'New Traditions' Curriculum Project carried out at the University of Wisconsin-Madison (1997). The 'New Traditions' project aimed to reform the chemistry curriculum, "...such that students obtain a deeper learning experience, improve their understanding and ability to apply learning to new situations, enhance their critical thinking and experimental skills, and increase their enthusiasm for science and learning." As such, the ACS General Chemistry Special Examinations were intended to contain a mixture of traditional and conceptual chemistry questions. The questions on these exams were developed by a group of chemical educators, and covered the range of topics and types of questions representative of the general chemistry curriculum, so these exams presented themselves as ideal instruments to use in developing a framework. In addition, the ACS exams were important instruments to analyze, because they are widely used by many institutions as testing instruments, and are the recognized gold standard in multiple-choice chemistry exams. Each of the General Chemistry Special Examinations was composed of forty multiple choice questions, with four possible responses to each of the questions.

We developed the framework by inspecting the general chemistry exam, and extracting key features of the different questions. The key features were related to the kind of information presented to the student in the questions, as well as the thinking process likely employed by the student. Once the framework was completed, we coded both the First Term and the Second Term General Chemistry Exams, assigning one or more codes to each of the questions in the exams, in order to validate the framework. The First Term General Chemistry Special Exam was coded by three coders, all of whom were instrumental in generating the codes. The inter-rater reliability was calculated by dividing the total number of correct codes by the sum of the total number of correct and incorrect codes. This reliability was determined to be 0.87, which is considered good (Borg and Gall, 1983). The Second Term General Chemistry Special Exam was also coded by three coders, and through training of the coders and one round of iteration, the inter-rater reliability was determined to be 0.84, which is considered good (Borg and Gall, 1983).

## Results and discussion

### The framework

As we developed the framework, primary and secondary levels of coding emerged, as shown in Fig. 1:

#### Primary levels of coding

The framework has three primary levels of coding: definition, algorithmic and conceptual. Definition questions (D) require students to recall, understand, apply, or recognize a definition. Algorithmic questions (A) require students to use information or processes that they have memorized. Conceptual questions

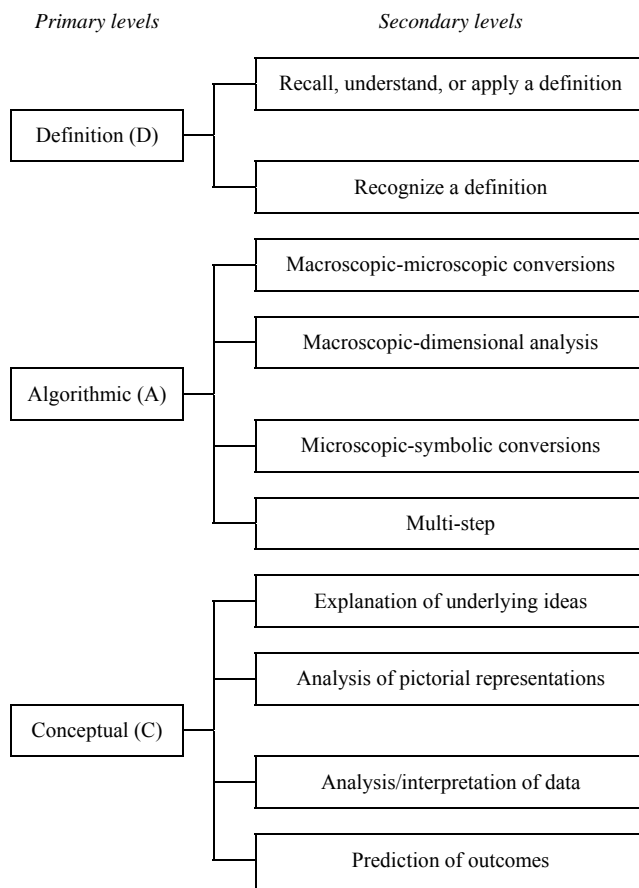


Fig. 1 Primary and secondary levels of the framework.

(C) require students to carry out some form of non-algorithmic analysis.

#### Secondary levels of coding

Each of the three primary levels of definition, algorithmic, and conceptual questions have secondary levels of coding. The example questions given in the following paragraphs were either constructed by the authors or cited on the website of the Journal of Chemical Education (<http://jchemed.chem.wisc.edu>); none of the questions were taken from any of the ACS exams.

##### Definition secondary levels

There are two secondary levels of coding under the primary level of definition coding: recalling, understanding, or applying a definition, and recognizing a definition. An important point of distinction between these secondary levels is that if a definition question is given as an open-ended question, it requires the student to recall the pertinent information, and/or understand and/or apply the definition. However, if a definition question is given in a multiple-choice format, then it requires the student to recognize the definition.

**Recall, understand, or apply a definition (D-RUA).** These questions are open-ended and require the recall, understanding, and/or application of a definition. For

example, the question: “Which particle inside the nucleus has a positive charge?” is coded as ‘D-RUA’ because it requires the students to recall the definition of the nucleus, and recall the name given to positive particles found within the nucleus.

**Recognize a definition (D-R).** These questions are multiple-choice and require the recognition of a definition. For example, the question :

Which particle inside the nucleus has a positive charge?

- a) neutron
- b) electron
- c) proton
- d) nucleon

is coded as ‘D-R’ because it requires the student to recognize that the term ‘proton’ is associated with positively charged particles inside the nucleus.

### Algorithmic secondary levels

Johnstone (1991) has suggested that chemistry students are expected to navigate three types of representations of chemistry: macroscopic (visible phenomena), sub-microscopic (invisible particles), and symbolic (formulas and equations). However, in this study, we refer to these representations as macroscopic, microscopic, and symbolic. In terms of algorithmic chemistry questions, these representations are displayed in calculations relating quantities involving the macroscopic level (volumes and masses), quantities involving the microscopic level (moles and numbers of particles), and chemical symbols (formulas and equations). These definitions of the various levels will be used in discussing the algorithmic part of this framework.

There are four secondary levels of coding under the primary level of algorithmic coding: macroscopic-microscopic conversions, macroscopic-dimensional analysis, microscopic-symbolic conversions and multi-step.

### Macroscopic-microscopic conversion questions (A-MaMi)

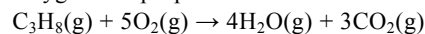
These questions require conversions between moles and macroscopic quantities (volumes or masses). For example, the question: “Given that the molar mass of iron is 55.85 g/mol, how many moles of iron are present in a 3.598 g iron nugget?” is coded as ‘A-MaMi’ because it provides the student with a macroscopic quantity (mass), with the requirement to convert the macroscopic quantity to a molar quantity through the familiar calculation of dividing the given mass by the molar mass to yield an answer of 0.06442 moles.

### Macroscopic-dimensional analysis questions (A-MaD)

These questions require conversions between units of macroscopic quantities. For example, the question: “A can of soda pop has a capacity of 12.0 oz. What is the capacity of this can in units of  $\text{cm}^3$ ?” is coded as ‘A-MaD’ because it provides a macroscopic quantity (volume) and requires the student to convert the units of the macroscopic quantity through the familiar process of dimensional analysis, using the conversion factor of 1 oz.:29.5  $\text{cm}^3$  (US measures), resulting in an answer of 354  $\text{cm}^3$ .

**Microscopic-symbolic conversion questions (A-MiS)** These questions require stoichiometric conversions of particle or mole quantities of substances, usually based on chemical formulas or equations. For example, the question:

Given the following balanced equation for the reaction between oxygen and propane:



how many moles of oxygen are required to completely burn 3.6 moles of propane?

is coded as ‘A-MiS’ because it provides a quantity of moles, and requires the student to carry out the familiar process of comparing molar coefficients to convert given moles of one substance into moles of another substance, yielding an answer of 18 moles of oxygen.

**Multi-step questions (A-Mu)** These questions include exercises and problems (Zoller and Pushkin, 2007), and involve multiple steps, frequently based on the use or algebraic manipulation of mathematical formulas. For example, the question: “Suppose you have 135.5 mL of 0.0289M  $\text{H}^+(\text{aq})$ . What is the pOH of this solution?” is coded as ‘A-Mu’ because it provides a value of molarity, and requires the student to substitute this value of molarity into one familiar equation (either  $\text{pH} = -\log[\text{H}^+]$  or  $[\text{H}^+][\text{OH}^-] = 1.0 \times 10^{-14} \text{M}^2$ ), then use the resulting value in another familiar equation ( $\text{pH} + \text{pOH} = 14$  or  $\text{pOH} = -\log[\text{OH}^-]$ ), resulting in a calculated pOH of 12.46.

### Conceptual secondary levels

There are four secondary levels of coding under the primary level of conceptual coding: explanation of underlying ideas, analysis of pictorial representations, analysis/interpretation of data and prediction of outcomes.

### Questions involving the explanation of underlying ideas behind chemical phenomena (C-E)

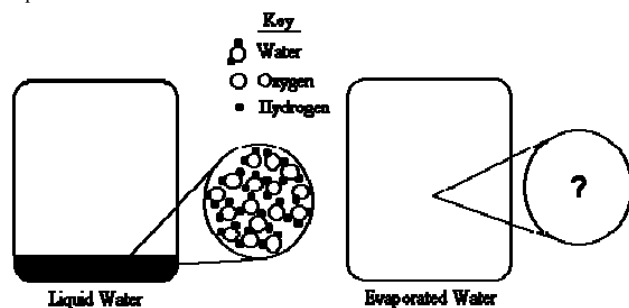
These questions present observations of a chemical phenomenon and require an explanation of the phenomenon. For example, the question: “When salt is dissolved in water the boiling point of the water increases. What is the best explanation for this?” is coded as ‘C-E’ because it identifies a chemical phenomenon, boiling point elevation, and requires the student to provide an explanation for it in terms of the dissolved ions disrupting the homogeneity of the water and decreasing the likelihood of the vaporization of water molecules.

### Questions involving the analysis of pictorial representations of chemical symbols or equations (C-P)

These questions present a pictorial representation of chemical symbols or equations and require an analysis of the situation. For example, the question (Figure 2), suggested by Robinson and Nurrenbern (n.d.b), via Robinson and Mulford (2002) for which the correct answer is choice e, is coded as ‘C-P’ because it provides a pictorial representation of water molecules in the liquid phase, and requires the student to analyze the pictorial representation, and recognize that as water evaporates covalent bonds are not broken or formed, and matter does not cease to exist.



The circle on the left shows a magnified view of a very small portion of liquid water in a closed container.



What would the magnified view show after the water has evaporated?

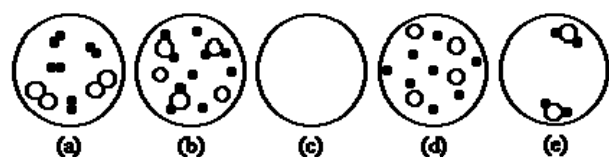


Fig. 2 An example of a “C-P” question.

Table 2 Sample Data for a “C-I” Question

$n^{\text{th}}$ ionization	ionization energy / $\text{kJ}\cdot\text{mol}^{-1}$
1 <sup>st</sup>	7,856
2 <sup>nd</sup>	9,012
3 <sup>rd</sup>	10,820
4 <sup>th</sup>	12,593
5 <sup>th</sup>	15,345
6 <sup>th</sup>	17,811
7 <sup>th</sup>	57,252

### Questions involving the analysis or interpretation of data (C-I)

These questions provide data in the form of a table, graph or qualitative descriptions, and require an analysis or interpretation of the data. For example, the question: “Identify the Period 2 element having the following values of successive ionization energies (Table 2)” is coded as ‘C-I’ because it provides a table of successive ionization energies, and requires the student to interpret the table of data. The student should realize that a relatively large increase in successive ionization energy occurs after the sixth electron has been removed, indicating a move to the inner shell of electrons for the removal of the seventh electron. This analysis should point to oxygen as the target element.

### Questions involving the prediction of outcomes (C-O)

These questions present a chemical situation and require the prediction of an outcome. For example, the question: “When an iron nail rusts, how will the mass of the rusted nail compare to that of the original nail?” is coded as ‘C-O’ because it provides a chemical scenario, the rusting of an iron nail, and requires the student to predict how the rusting will affect the mass of the nail, by recognizing that rusting is both an oxidation and a combination chemical reaction, adding mass to the iron nail.

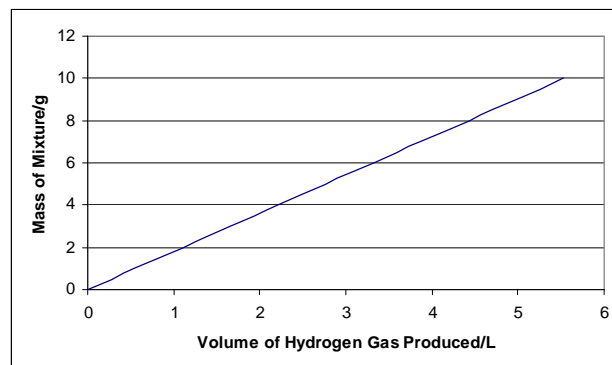


Fig. 3 A sample graph for a question with multiple codes.

### Questions involving combinations of codes

Some questions can be assigned multiple codes. Demanding general chemistry questions sometimes involve both algorithmic and conceptual components, and these types of questions would fall into the category of higher-order cognitive skills (HOCS) questions (Zoller *et al.*, 1995), higher order questions (Robinson and Nurrenbern, n.d.a), or problem solving questions (Hanson and Wolfskill, n.d.a). For example, the question: “Several samples of a finely ground mixture of magnesium and aluminum are reacted with excess hydrochloric acid at room temperature to produce hydrogen gas. Use the resulting graph (Fig. 3) to determine the mass percent of magnesium in the mixture” can be solved by setting up a system of two simultaneous equations: the first relates the sum of the unknown masses of Mg and Al to the mass of the sample, using a point on the y-axis; the second uses the same point on the y-axis and the corresponding point on the x-axis to yield an equation relating the sum of the unknown moles of Mg and Al to the moles of hydrogen gas produced, after the appropriate conversions. This system of two simultaneous equations can then be solved to yield the mass composition of the mixture, 20% magnesium and 80% aluminum. This question requires students to analyze a graph (C-I), convert gas volumes to moles (A-MaMi), convert between masses and moles (A-MaMi), carry out stoichiometric mole-mole conversions (A-MiS), and engage in multiple steps (A-Mu). This question has four types of components: C-I, A-MaMi, A-MiS, and A-Mu. We estimate the composition of this question to be 75% algorithmic and 25% conceptual, based on the types of algorithmic and conceptual components present in the question.

### Composition of the ACS Special Exams

The compositions of both the First Term and the Second Term General Chemistry Special Examinations in terms of the primary level of coding are given in Table 3. The composition of each exam was determined by coding each question on each exam, calculating the composition of each question in terms of a percentage of definition, algorithmic and conceptual as outlined above, and determining the overall composition of each exam. The reliability of coding was determined to be 0.84, which is considered good (Borg and Gall, 1983).

**Table 3** Average composition of the ACS Special Exams

Question components	First term exam	Second term exam
Definition (D)	24%	38%
Algorithmic (A)	23%	16%
Conceptual (C)	53%	46%

We propose that definition and algorithmic components can be considered as traditional components; therefore, both exams contained approximately equal proportions of traditional and conceptual components. These exams were designed to have a mixture of traditional and conceptual components, and the framework shows that this goal was obtained.

## Conclusions

The framework we developed has been applied to ACS exams, with results which strengthen its validity. This framework has also been used to investigate chemistry faculty's cognitive expectations about learning chemistry and its influence upon their construction of exam questions in a general chemistry curriculum (Sanabria-Rios and Bretz, 2010). Therefore, we argue that this framework could prove useful to chemical educators in creating new exams or modifying existing exams. Our framework could also be used by researchers interested in further exploring issues related to the nature of questions in student performance in general chemistry.

## Acknowledgements

We gratefully acknowledge funding for this project provided during the evaluation of the project entitled: 'Professional Development for High School Chemistry Teachers: Integrating Pedagogy and Content through Teacher Research' (FIPSE Grant #P116B011231), for which the principal investigator was Stacey Lowery Bretz. We thank and acknowledge the coders involved in this project: Debbie Herrington, Sarah Freemyer, Larry Miller, Brian Postek, and John Polles, who are all present or past members of the Nakhleh Group at Purdue University. We also thank and acknowledge Thomas L. McLean at the Statistical Consulting Service of Purdue University for his thoughtful insight and suggestions.

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