

Classification of End-of-Chapter Questions and Problems in General Chemistry Textbooks Used in the US

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Abstract

Science textbooks have a major influence on teaching and learning. Teachers and instructors at all educational levels use them regularly not only as a guide for course content and sequence, but also in the design of homework assignments and assessment probes. From this perspective, textbook questions and problems can be expected to have a strong influence on assessment practices in the science classroom. Thus, the main goal of this study was to investigate the nature of end-of-chapter questions and problems included in college general chemistry textbooks, and discuss the implications of this analysis for teaching and learning in introductory chemistry courses. Our results indicate that commonly used general chemistry textbooks include a majority of questions and problems at the “Application” and “Analysis” levels as defined using Bloom’s cognitive categories. These items tend to be narrowly focused on certain specific types. For example, problems at the “Application” level are mainly algorithmic, while questions at the “Analysis” level are mostly inferences and predictions. There are much fewer exercises that require students to translate between different levels of representation, compare or correlate data, concepts, or ideas, or apply their knowledge and understanding to make hypothesis, create models, or make critical judgments.

Keywords: First-Year Undergraduate/General, Curriculum, Chemical Education Research, Textbooks

Introduction

Science textbooks have a strong influence on curriculum, instruction, and assessment at all educational levels, and thus have been the object of a variety of research studies (1-3). In the case of college introductory chemistry, the role of the textbook is so prominent that discussions about curriculum are frequently intertwined with the evaluation of the “prototypical textbook:” an instructional resource that is assumed to have a relatively fixed topic structure and educational philosophy independently of the authors (4-9). Analysis of the general chemistry textbook is thus of central importance if one is interested in understanding, for example, the nature and relevance of the course content or the types of learning that are valued in the discipline.

Analysis of introductory chemistry textbooks at the secondary and college level in the past few years have mostly focused on content, language, and representational issues. These research studies include investigations on views of the nature of science as portrayed by the presentation of specific topics (10-11), the role of analogies (12-13), the nature of explanations (14), the source of errors and misconceptions (15-16), the educational impact of illustrations and other forms of representation (17), the social relevance of selected content (18), and the analysis of diversity and equity issues (19-20). To our knowledge, there are no studies that have focused on the nature of the questions and problems traditionally included at the end of the chapters in introductory chemistry textbooks. This investigation is crucial to develop a better understanding

of the types of knowledge that are valued in chemistry teaching. In general, textbook questions and problems can be expected to have a strong influence in what is assessed and how it is assessed in the chemistry classroom, and to act as powerful tools in directing students' attention (21) and communicating learning objectives and expectations. Thus, the main goal of this research study was to investigate the nature of end-of-chapter questions and problems included in college general chemistry textbooks, and discuss the implications of this analysis for teaching and learning in introductory chemistry courses.

Textbooks in Science Education

Research in many countries, in different contexts and educational levels, has shown that textbooks have a major influence on teaching and learning (22-23). Studies of textbook usage in the past three decades have been consistent in their results. With relatively small variations depending on grade level and subject matter, 70% to 95% of activities in K-12 US classrooms were estimated to rely on textbooks for planning and teaching purposes (24-26). Although no equivalent information seems to be available for the college level, well-known traditional practices at a variety of institutions of higher education suggest similar patterns of textbook usage in courses in the physical sciences.

Science teachers' attitudes towards and preferences for science textbooks have also been investigated (27-30). Research results suggest that although science teachers do not have consistent expectations from texts, the item "textbook questions and problems" is systematically reported as one of the top features in the list of teachers' relevant criteria for textbook selection (27-28, 30). A comparative study of science teachers' and students' perceptions of textbook usage (31) revealed that students tended to believe that textbooks were used to a greater extent than teachers believe was the case; both students and teachers perceived that the main use of the science textbook was for assigning homework and for in-class activities. All of these studies underscore the importance of analyzing the types of questions and problems included in science textbooks and the corresponding implications for teaching and learning.

The role of textbook questions in student learning has been analyzed by several authors. For example, Holliday (21) elicited the important function that study questions have on focusing students' attention, while Leonard (32) highlighted the role of in-text questions in assisting student learning. Low-level cognitive questions have been shown to over promote students' attention to information specific to the question, reducing learning effectiveness of other concepts and ideas (33). On the other hand, higher-level cognitive questions seem to broaden students' attention to textual information (34). Unfortunately, analysis of several high school science textbooks indicates that low-level cognitive questions tend to be predominant (35). In the particular case of college chemistry, the consequences of the overuse of questions and problems that focus on algorithmic and low-order cognitive skills versus higher-level thinking have been described by a variety of authors (36-38).

Goals, Sources, and Data Analysis

Our study was guided by the following research questions:

- What types of end-of-chapter questions and problems are included in commonly used college general chemistry textbooks in the US?
- What are the major differences, if any, in the types of end-of-chapter questions and problems among commonly used college general chemistry textbooks in the US?

The answers to these questions were built through the analysis and categorization of the end-of-chapter questions and problems presented in the three top-selling college general chemistry textbooks in the US (39-41). According to data provided by the textbook publishers, when combined, the analyzed general chemistry textbooks share over 50% of the market, and thus are used by thousands of students in the US.

Questions and problems were classified using the original and revised Bloom's taxonomies of educational objectives (42). We decided to use this taxonomy for a variety of reasons: it has been applied by many authors to classify learning objectives, test items, problems, and questions, and thus it is widely known across the education community; it provides a commonly understood meaning to items classified in its various categories; it is based on a clear hierarchical cognitive framework from simple to complex and from concrete to abstract. Our analysis focused on the majority of the questions and problems included at the end of the seventeen chapters traditionally covered in a one-year general chemistry course for science and engineering majors in the US (See Supplemental Materials); the only questions and problems excluded from the analysis were those that required the use of additional multimedia resources. Many of the end-of-chapter questions and problems in the analyzed textbooks included multiple sub-questions; in these cases, every sub-question was individually coded and classified.

In order to assess and ensure the reliability of our classification system, we started the process by agreeing on an initial categorization scheme based on the analysis of randomly selected problems. Then, both authors independently analyzed one randomly selected chapter and classified all of its end-of-chapter problems and questions. In the next step, the authors' assignments for every item were compared, discussing the cases where there was disagreement and negotiating a final category code for the corresponding question or problem. This process was repeated with the necessary number of randomly selected chapters until we were able to reach a minimum of 90% agreement. After this point, each author independently analyzed and categorized the problems of assigned chapters.

Results

The analysis of the targeted textbooks elicited the major types of end-of chapter questions and problems listed in Table 1, where we present them arranged in categories based on a conventional Bloom's taxonomy of educational objectives. The basic characteristics of the types of questions and problems that were identified within each of these categories are summarized in the following paragraphs.

- *Recalling*. Refers to questions or problems in which students are asked to provide an answer based on remembered information, such as defining a concept, describing a phenomenon, or listing, naming, or recognizing different types of chemical substances or reactions.
- *Finding*. Students are asked to find specific information in the textbook or in other sources.
- *Translating Particulate* $\leftarrow \rightarrow$ *Symbolic*. These types of problems require that the students translate a representation from particulate to symbolic forms, or vice-versa.
- *Representing*. The task requires representing data or processes in graphical or symbolic forms.
- *Interpreting*. The task is centered in interpreting information presented in various forms (graphical, symbolic, or any other forms of representation).
- *Classifying*. The students are asked to categorize chemical substances, reactions, or interactions described or represented in various forms (macroscopic, particulate, symbolic).
- *Explaining*. The students are asked to justify an answer or offer reasons for a decision.

Table 1. Types of questions and problems in college general chemistry textbooks

Cognitive Category	Types of questions or problems	Examples
Knowledge	Recalling	Give the name or chemical formula, as appropriate, for each of the following acids: a) HBrO_3 , ..d) iodic acid...
	Finding	Consult a handbook of chemical and physical data to find: a) two metals less dense than water, ...
Comprehension	Translating Particulate $\leftarrow \rightarrow$ Symbolic	Which of the following equations best represents the reaction shown in the diagram: a) $A + B \rightarrow C + D$; b) $6A + 4B \rightarrow C + D$;
	Representing	The boiling point and freezing point of sulfur dioxide are -10°C and -72.7°C (at 1 atm), respectively.....On the basis of this information, draw a rough sketch of the phase diagram of SO_2 .
	Interpreting	Match the following descriptions of titration curves with the diagrams: a) strong acid added to strong base,....
	Classifying	Which of the following diagrams is most likely to represent an ionic compound?
	Explaining	Why is the change in enthalpy usually easier to measure than the change in internal energy?
Application	Executing-Quantitative	Calculate a) the number of grams of solute in 0,250 L of 0.150 M KBr.
	Executing-Qualitative	<ul style="list-style-type: none"> Draw the Lewis structure for the following molecules or ions: a) PF_3,... Write the condensed electron configurations for the following atoms: a) Ga,...
Analysis	Comparing	What are the differences and similarities between Figure 20.3 and Figure 20.4?
	Inferring/Predicting	Place the following substances in order of increasing volatility: CH_4 , CBr_4 ,...
Synthesis	Designing	By using a reaction flask, a manometer, and any other common laboratory equipment, design an experimental apparatus to monitor the partial pressure of $\text{H}_2(\text{g})$ produced as a function of time.
Evaluation	Evaluating	When asked to calculate the molar solubility of $\text{Mg}_3(\text{AsO}_4)_2$ in water, a student assumed..... Why was this a mistake?

- *Executing.* The questions or problems require the application of specific algorithms or procedures to generate an answer. The algorithm could require *quantitative* reasoning or *qualitative* reasoning.

- *Comparing*. The task requires comparing the properties different systems (e.g. arranging substances in order of increasing boiling point or solubility in water).
- *Inferring/Predicting*. The students are asked to draw inferences or make predictions about the properties or behavior of a system based on information provided and their own knowledge.
- *Designing*. Students are asked to design a procedure to solve a problem or demonstrate an idea.
- *Evaluating*. The question requires students to assess the veracity of a statement or critique an idea or procedure.

The distribution of all of the end-of-chapter questions and problems among these different types is presented in Table 2, where we show the percentage of questions and problems of each type, as well as the total number of items analyzed (n), for each of the selected general chemistry textbooks. The data indicates that there are five major types of questions and problems commonly used in the three analyzed textbooks: Executing-Quantitative, Executing-Qualitative, Inferring/Predicting, Explaining, and Recalling; all of the other types of questions and problems are present in much lower proportions. However, analysis of the data using a Chi-Square test revealed that there was a statistically significant difference in the use of these five major types of questions and problems among the three textbooks ($\chi^2 = 242.7$; $df = 4$; $p < 0.001$).

To identify which of the major types of questions and problems were the main contributors to this significance, we performed a post hoc test to evaluate the standardized residuals for each problem type. Using a level of significance of 0.05 we found contributions to this significance mainly associated with: a) Chang's textbook overuse of "recalling" questions and underuse of "executing-quantitative" and "inferring/predicting" types; b) Silberberg's overuse of "executing-quantitative" and underuse of "recalling" and "explaining" types, and c) Brown's overuse of "inferring/predicting" and underuse of "executing-qualitative" types. In this sense, our analysis revealed somewhat different emphases in the three textbooks, with Chang's favoring questions and problems in the "Knowledge" category, Silberberg's emphasizing the "Application" category, and Brown's focusing slightly more on the "Analysis" category.

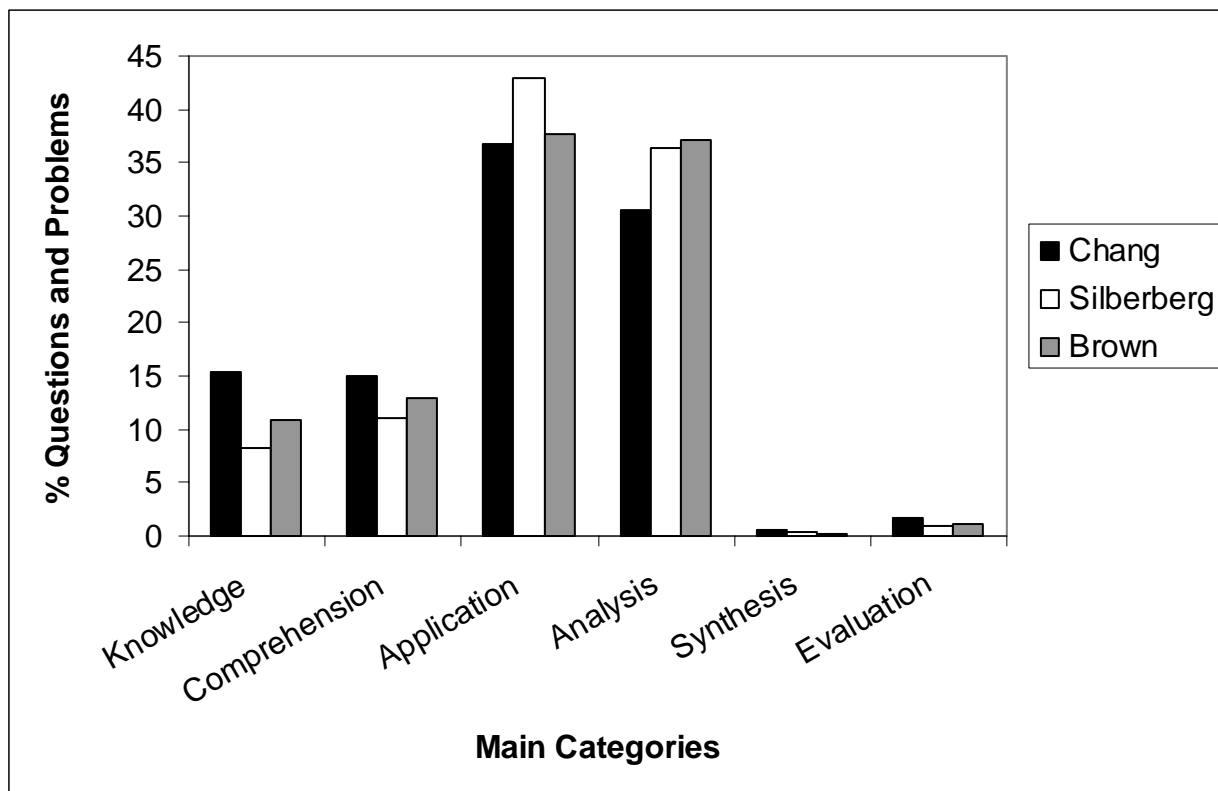
Similarities and differences among the three textbooks can be better appreciated in Figure 1, where we depict the corresponding percentages of questions and problems in different cognitive categories as defined by Bloom and Krathwohl (42). This figure highlights the central role that "Application" questions and problems, which mainly target algorithmic problem solving skills in this case, have in all of the textbooks (39.3% of the total number of questions and problems analyzed). Analysis of the data in Table 3 shows that more than three quarters of this set of problems tend to be quantitative in nature (77.0% of the total number of problems in this category), but also reveals the existence of a significant proportion of algorithmic problems in chemistry textbooks that require the application of non-mathematical procedures (Executing-Qualitative).

Questions and problems in the "Analysis" category correspond to the second major group of items in the analyzed textbooks (34.9% of the total number of problems analyzed). Most of the questions in this category are of the "inferring/predicting" type (95.2%). The combination of "Analysis" and "Application" questions and problems constitute over three quarters of the items in most of the chapters in the three textbooks (see Supplemental Materials). Although "inferring/predicting" types of questions have an important presence in every textbook chapter, they are particularly predominant in chapters that address the topics of chemical bonding, molecular geometry, and intermolecular forces. On the other hand, "executing" types of problems are more widespread, being the larger group of problems in 50% (Brown's) to 75% (Chang's) of the analyzed chapters in the different textbooks.

Table 2. *Distribution of end-of-chapter questions and problems among the different types and categories listed in Table 2.*

	Knowledge		Comprehension					Application		Analysis		Synth.	Eval.	Total n
	Recall %	Find. %	Trans. %	Repr. %	Inter. %	Class. %	Expl. %	E. Qt. %	E. Ql. %	Comp. %	Inf/Pr. %	Des. %	Eval. %	
Chang	14.9	0.58	0.61	0.88	0.94	4.63	7.93	27.3	9.44	1.62	29.0	0.53	1.69	6050
Silberberg	8.23	0	1.04	0.94	0.41	1.88	6.87	33.2	9.63	2.17	34.3	0.46	0.89	7341
Brown	10.6	0.34	1.12	0.14	1.26	1.91	8.49	29.7	8.01	1.15	35.9	0.26	1.15	6453

Figure 1. Percentage of the total number of questions and problems in the major categories listed in Table 2 (Bloom’s taxonomy) for each of the textbooks analyzed.



End-of-chapter questions and problems in the “Knowledge” and “Comprehension” cognitive categories have similar weights within a given textbook and each of them corresponds to 10% to 15% of all of the items. Interestingly, most of the questions and problems in the “Knowledge” category are of the “recalling” type (97.5%), while a large proportion of the items in the “Comprehension” category correspond to questions that ask students to explain their answer or reasoning (59.9%). Surprisingly, these general chemistry textbooks only allocate around 1% of their items to questions and problems that require students to translate between different levels of representation (particulate \leftrightarrow symbolic); these textbooks include similarly small percentages of questions that ask students to interpret or represent information in graphical or symbolic forms. These low percentages are also common for questions and problems in the “Synthesis” and “Evaluation” categories, which consistently correspond to the least used type of questions and problems in all of the analyzed chapters in each textbook.

Discussion and Implications

Our analysis revealed that commonly used general chemistry textbooks tend to include a majority of questions and problems at the “Application” and “Analysis” levels as defined using Bloom’s cognitive categories. These could be considered as questions and problems at an intermediate level of cognitive demand. They also correspond to “processing” questions in Costa’s classification scheme based on an information processing model (43). Processing questions demand that students draw meaningful relationships among data that is provided or

must be recalled (questions and problems at the “Comprehension” level can also be included in this category). They differ from “input” questions which require students to simply recall information or derive it from sensory data (Knowledge level in Bloom’s taxonomy), and from “output” questions that ask students to go beyond the concepts and principles that they have developed and to use their knowledge in novel situations (Synthesis and Evaluation levels in Bloom’s taxonomy).

One can argue that questions and problems at intermediate levels of cognitive demand may be certainly the most appropriate to include in introductory textbooks for any scientific discipline at the college level. However, our analysis of general chemistry textbooks shows that the end-of-chapter questions and problems within different cognitive categories tend to be narrowly focused on certain specific types. For example, problems at the “Application” level are mainly algorithmic, while questions at the “Analysis” level are mostly inferences and predictions, with much fewer questions asking students to compare, contrast, or correlate data, concepts, or ideas. At the “Comprehension” level, explanations are clearly dominant in these textbooks over questions that require students to translate, interpret, and represent data or information in multiple forms. Despite the multiple calls from science and chemical educators to create opportunities for students to learn how to navigate between the macroscopic, particulate, and symbolic ways of describing the world in Chemistry (44-46), no more than 1% of the questions in the analyzed textbooks target this skill. Given that textbooks are the major source of exercises assigned and available to the students, we should not then be surprised by their inability to comfortably move between these different levels of description and analysis.

Our study also shows that although a large fraction of the end-of-chapter questions and problems in the analyzed textbooks involve algebraic or numeric problem solving (Executing-Quantitative), a significant proportion either require the application of qualitative rules or procedures (Executing-Qualitative) or demand drawing inferences and making predictions. The research literature in problem-solving in chemistry has been often focused on the dichotomy in students’ performance on “conceptual” versus “algorithmic” problems (37, 47). However, the definition of “conceptual” questions or problems is commonly restricted to questions involving particulate representations of matter (48), while “algorithmic” problems are typically conceived as numerical exercises. Our results underscore the need to expand our conceptualization of the types of questions and problems that are relevant in learning chemistry (such as those involving classifications, comparisons, inferences, and predictions, as well as non-numerical algorithms), and promote the development of research studies that investigate how students approach this type of non-mathematical or qualitative problem-solving, what difficulties they face, and what strategies help them improve their performance.

Despite significant differences in the distribution of major types of problems in the three textbooks that were analyzed, “executing-quantitative” and “inferring/predicting” types of questions and problems are predominant in all of them. One may thus suspect that similar types of assessment items will characterize homework assignments, and midterm and final exams in introductory chemistry courses. To verify this hypothesis, we applied our classification scheme to the multiple choice questions included in a recent version of a standardized final exam for the first semester of general chemistry designed by the American Chemical Society Exam Institute. This analysis gave the following distribution of categories of question and problems: Knowledge, 11.5%; Comprehension, 13.5%; Application, 41.3% (with 58.1% in the executing-quantitative and 41.9% in the executing-qualitative types); Analysis, 30.8% (93.8% of the inferring/predicting

type); Synthesis, 0%, and Evaluation, 2.88%. These results are within the same ranges as those described for the three analyzed textbooks.

Our results suggest that instructors would benefit from recognizing the types and categories of textbook end-of-chapter questions and problems as identified in our work to try to diversify the pool of items that they use for practice and assessment purposes. Beyond the inclusion of more questions that ask students to translate or interpret particulate representations of matter, which certainly are needed, we must recognize the serious lack of problems in the higher cognitive categories (Output, or Synthesis and Evaluation levels) that require students to apply what they have learned in new contexts, and to use their knowledge and understanding to make hypothesis, create models, design experiments, generalize ideas, and make critical judgments. These types of questions and problems are practically inexistent in the analyzed textbooks, which likely limits students' opportunities to develop more meaningfully and lasting understandings.

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Supplemental Materials

Our analysis of the selected textbooks focused on the majority of the questions and problems included at the end of the seventeen chapters traditionally covered in a one-year general chemistry course for science and engineering majors in the US. Table 1 in these supplemental materials lists the names of the analyzed chapters, together with the label assigned to each chapter for reference purposes. The only questions and problems excluded from our analysis were those that required the use of additional multimedia resources. Many of the end-of-chapter questions and problems in the analyzed textbooks included multiple sub-questions; in these cases, every sub-question was individually coded and classified.

Figures 1a, 1b, and 1c in this supplemental materials show the distribution of categories of questions and problems (according to Bloom's taxonomy), for each of the analyzed chapters in Chang's, Silberberg's, and Brown's textbooks, respectively. The labels assigned to each chapter correspond to those introduced in Table 1 of these supplemental materials. These graphs reveal both qualitative and quantitative differences and similarities in the types of questions and problems that different authors include in textbooks chapters with similar content.

Table 1. Set of analyzed textbook chapters and assigned labels.

Brown, LeMay, & Bursten 10th Edition	Chang, 9th Edition	Silberberg, 4th Edition	Label
Atoms, Molecules, and Ions	Atoms, Molecule, and Ions	The Components of Matter	AMI
Stoichiometry	Mass Relationships in Chemical Reactions	Stoichiometry of Formulas and Equations	S
Aqueous Reactions and Solutions Stoichiometry	Reactions in Aqueous Solutions	The Major Classes of Chemical Reactions	AR
Thermochemistry	Thermochemistry	Thermochemistry	T
Electronic Structure of Atoms	Quantum Theory and Electronic Structure of Atoms	Quantum Theory and Atomic Structure	ES
Periodic Properties of Elements	Periodic Relationships among the Elements	Electron Configuration and Chemical Periodicity	PP
Basic Concepts of Chemical Bonding	Chemical Bonding I	Models of Chemical Bonding	CB
Molecular Geometry and Bonding Theories		The Shapes of Molecules	MG
Gases	Gases	Gases and the Kinetic-Molecular Theory	G
Intermolecular Forces, Liquids, and Solids	Intermolecular Forces and Solids and Liquids	Intermolecular Forces	IMF
Properties of Solutions	Physical Properties of Solutions	The Properties of Mixtures	PS
Chemical Kinetics	Chemical Kinetics	Kinetics	CK
Chemical Equilibrium	Chemical Equilibrium	Equilibrium	CE
Acid-Base Equilibria	Acids and Bases	Acid-Base Equilibria	AB
Additional Aspects of Aqueous Equilibria	Acid-Base Equilibria and Solubility Criteria	Ionic Equilibria in Aqueous Systems	AE
Chemical Thermodynamics	Entropy, Free Energy, and Equilibrium	Thermodynamics	CT
Electrochemistry	Electrochemistry	Electrochemistry	E

Figure 2. Distribution of questions and problems in the major categories of Bloom's taxonomy for each of the chapters analyzed in a) Chang's, b) Silberberg's, and c) Brown's textbooks. The labels assigned to each chapter correspond to those introduced in Table 1 of these supplemental materials.

