A Historical Analysis of the Curriculum of Organic Chemistry Using ACS Exams as Artifacts

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Abstract
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Keywords
second-year undergraduate, organic chemistry, testing/assessment

Disciplines
Curriculum and Instruction | Higher Education | Other Chemistry | Science and Mathematics Education

Comments
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ABSTRACT: Standardized examinations, such as those developed and disseminated by the ACS Examinations Institute, are artifacts of the teaching of a course and over time may provide a historical perspective on how curricula have changed and evolved. This study investigated changes in organic chemistry curricula across a 60-year period by evaluating 18 ACS Organic Chemistry Exams through the lenses of problem-type, visualization use, content covered, and percentile rankings. For all lenses, the early 1970s emerged as a focal point for change and stabilization of the organic chemistry curricula.

KEYWORDS: Second-Year Undergraduate, Organic Chemistry, Testing/Assessment

INTRODUCTION

For almost 80 years, the American Chemical Society’s Division of Chemical Education has sponsored the development of standardized chemistry exams. Examinations now span the breadth of chemistry subdisciplines (e.g., physical chemistry, biochemistry, inorganic chemistry, etc.) and specialized courses (e.g., General–Organic–Biochemistry combined courses). Examinations are routinely rewritten and revised by committees of faculty volunteers. Because of the grassroots manner in which the exams are prepared, this means for most subdisciplines of chemistry, such as organic chemistry, that there are standardized examinations across a number of years that can serve as a historical record of the curriculum. One such record has been investigated for physical chemistry by Schwenz, and reported in the Advances in Teaching Physical Chemistry ACS Symposium Series. This paper describes work that follows a similar methodology in analyzing organic chemistry exams.

The current study considers a 60-year history of organic chemistry covering 18 examinations. A summary of guiding curricular documents for organic chemistry courses helps establish the stage for this analysis, which is presented by first describing the examinations sampled for the study, and then the findings. Findings emerged from the analysis of the examinations using these four lenses:

1. An algorithmic, conceptual, recall problem typology
2. Use of representations in the prompt and answer options
3. Content covered
4. Percentile rankings

ACS Examinations as Pedagogical Artifacts

The ACS Exams Institute development process has been previously described. A key component of this process is that not only do volunteers who teach the course for which the exam is constructed write items, but the development committee also determines the topics covered. As such, ACS exams generally reflect the content coverage of the prevalent course curriculum at the time of their construction. The frequency of this process is generally correlated with the number of exams sold and the number of institutions using the exam. As will be seen for the organic chemistry exams, new exams are generally developed every four years. For comparison, new exams are developed for general chemistry every two years and physical chemistry exams are typically on a five-year sequence. Examination writers generally serve for the development of one or two exams unless they become the examination committee chair, which often involves serving on a third committee; approximately half of each examination committee is composed of previous examination writers. Therefore, there are always elements of consistency and newness to each examination committee.

What this process represents, therefore, is a means by which artifacts of the extant curriculum are devised. While textbooks are likely more influential artifacts in terms of setting the limits on content coverage, ACS exams represent a more realistic view of the breadth of actual coverage at any moment in time. Many view the modern textbook as too encyclopedic, and seldom covered in its entirety. While ACS exams may also include a broader range of content than is covered in any individual course, they nonetheless provide a fair picture of content coverage in an aggregate sense. If items are from material that is not widely covered, they would not have psychometric properties during trial testing that would merit their inclusion in the final, released version of the exam.

Current ACS exams follow a multiple-choice examination format using either four or five answer options. The item prompt sometimes includes relevant data (i.e., graphs, tables of data, or molecular representations). Noncorrect answer options, also referred to as distractors, are developed by the examination writing committee to represent answers that a student would select, for example, based on incorrect

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interpretation of the prompt or common algorithmic calculation mistakes. The range of all ACS Exams includes instruments with 40–120 items, though most have either 60 or 70 items.

■ ORGANIC CHEMISTRY CURRICULUM

Yearlong organic chemistry curricula in the United States appear to have remained rather consistent since the publication of a pair of articles in the Journal of Chemical Education in the early 1970s.6,7 These articles outlined a set of topics and curricular themes that are still found in most major organic chemistry textbooks. Content topics begin with an introduction to molecular structure and properties (such as acidity and boiling point); simple reactions of alkanes, alkenes, and alkynes; substitution and elimination reactions; spectroscopy; carbonyl chemistry; and conclude with nitrogen-containing compounds and an introduction to biochemistry. These content areas are similar to a recent mapping of the organic chemistry curriculum reflective of the current state of organic chemistry instruction.11 The analysis of the ACS Organic Chemistry Exams presented here will provide one way to envision how this content coverage has developed over time.

■ ACS DIVCHED ORGANIC CHEMISTRY EXAMS

The ACS Examinations Institute has produced 22 organic chemistry examinations dated back to 1942. Combined, these examinations include 1830 individual exam items, with 70–100 questions per exam. ACS Exams are secure tests, and as such are not published works in terms of copyright, but rather are released for use by the chemical education community. The 2008 and 2012 Organic Chemistry Exams are still considered active, and each contains 70 questions. The first four exams (1942, 1943, 1944, and 1946) include items beyond the traditional four or five answer options for multiple-choice items found on current exams; for appropriate comparisons to be rendered, these exams were excluded from the analyzed data set. Therefore, the analysis reported here derives from 18 ACS Organic Chemistry Exams from 1949 to 2012, representing 1440 individual exam items.

■ CHANGES IN THE EXAMS OVER TIME

Four frameworks were used to analyze the ACS Organic Chemistry Exams. The first model considers items divided into algorithmic, recall, conceptual problem types. This model has shown promise in understanding ACS General Chemistry Exams8 and a collection of curricular problems from four yearlong organic chemistry courses.9 Using this framework suggests that ACS Organic Chemistry Exams have become more conceptually based over the 60-year period. The second framework considers the use of representations in the exam prompts, answers, and distractors. The use of representations is synonymous with organic chemistry research practice;10 several recent educational research initiatives in organic chemistry and biochemistry have focused on student understanding of representations.14 In the case of Organic Chemistry Exams, they have progressed from representation use in very few items to representation use in almost every item. The third framework was content coverage of each exam item using the content categories of the ACS Organic Chemistry Exam Study Guide.15 Content categories were expanded to account for content on earlier exams that were not intended to be covered by the current study guide. An expected finding from this framework was that the number of qualitative analysis exam items was replaced with spectroscopic exam items; this transition coincides with the development and integration of spectroscopic techniques into organic chemistry research practice. The final framework was of normed percentile rankings, a measure of the percentage of questions necessary to score at a given percentile. Scores at the 80th, 65th, 50th, and 35th percentile rankings were recorded; a marked shift in the difficulty of the exam occurred in the early 1970s. Each framework will be discussed further in this section and the understanding that may be inferred from this analysis of the exams will be described.

Algorithmic, Recall, Conceptual Model

Categorizing student learning according to the algorithmic versus conceptual nature of problems that can be solved has a long history in the chemical education research literature. Numerous studies have considered how students answer algorithmic versus conceptual problems in general chemistry.13–15 They have often found that students can successfully answer algorithmic problems without any apparent conceptual understanding. Raker and Towns9 posed the question as to whether such differences existed in organic chemistry, but this study was constrained by the challenge of defining what an algorithmic or conceptual problem is in organic chemistry. Their work nonetheless reported the operationalization of an algorithmic, recall, conceptual categorization scheme originally proposed by Nurrenburn and Robinson.16

In their scheme, algorithmic problems are considered to be any problem that required a stepwise procedure. Although this problem type is usually associated with numerical problems, organic nomenclature problems, for example, can be considered algorithmic because of the stepwise nature of composing a compounds name. Recall problems required a fact, such as a definition, as the answer. Conceptual problems are more complex. Robinson and Nurrenburn state that conceptual problems require the solver to:17

[J]ustify a choice, predict what happens next, explain why something happens, explain how something happens, link two or more areas or topics,.. [or] extract useful data from an excess of information.

Raker and Towns9 extended this idea so that problems in organic chemistry that include instructions such as these are considered conceptual problems for the purpose of the analysis described here.

Having established sufficient percentage-agreement inter-rater reliability (84.4%), Raker and Towns reported that 82% of 211 locally authored final exam organic chemistry problems were conceptual, 9% were algorithmic, and 9% were recall.9 These findings are dramatically different from an analysis of the 1997 First and Second Term ACS General Chemistry Special Exams (the original version of a paired questions exam18 produced by ACS Exams), which found 53% and 46% conceptual problems, 23% and 16% algorithmic problems, and 24% and 28% recall problems, respectively, on the two exams evaluated.8

There remains a fundamental limitation in this characterization of organic chemistry problems because the items were obtained from courses at a single institution, so it is not obvious...
that the categorizations will generalize to all organic chemistry courses. An analysis of the ACS Organic Chemistry Exams, which are developed by a committee of nationally distributed volunteers and taken by students nationwide, should provide a more representative depiction of problem types in second-year-level organic chemistry instruction.

The percentage of algorithmic, recall, and conceptual problems for each of the ACS Organic Chemistry Exams since 1949 is reported in Figure 1. Sample recall, algorithmic, and conceptual questions, taken from the Organic Chemistry Study Guide, are reported in Figure 2. Due to the constraints of secure copyright, actual examination items cannot be reported. From 1949 until approximately 1978, the trend for the percentage of conceptual exam items gradually increases until slightly more than 90% of the exam problems were conceptual in nature. This suggests that the Raker and Towns report of 82% may be underestimating the relative amount of conceptual problems used on organic chemistry assessments. Algorithmic problems account for 5% to 10% of exam items; these problems were mainly nomenclature problems, with two to three appearing on each ACS Exam. Finally, recall problems composed almost 40% of the 1949 exam and have declined to less than 5%. Most recent exams have at most one exam item that fundamentally hinge on students ability to recall a specific fact in order to obtain the answer.

Looking at this data and considering the reports from 40 years ago, the hypothesis of the relative stability of the organic chemistry curriculum appears confirmed. Particularly when considered through the lens of algorithmic, recall, and conceptual problem types on final examinations, there has been little variation for at least 30 years. Data reported in Figure 1 appears to be able to be divided between 1978 and 1982; problem types prior to this divide are changing and problems types after 1982 have stabilized. While it is difficult to establish a causal effect, the confluence of the 1970s articles and the apparent stabilization about problem types on the ACS Exams may imply that these articles helped usher in a consensus approach for teaching organic chemistry.

Figure 1. Percentage of algorithmic, recall, and conceptual problems on ACS Organic Chemistry Examinations.

Figure 2. Sample recall, algorithmic, and conceptual questions.

Representation Use

Chemists regularly use representations (e.g., chemical structures, tables of data) to communicate chemical knowledge. Anecdotally, it is reasonable to observe that the introduction of personal computers and sophisticated software technology has eased the incorporation of more representations into the chemical literature, textbooks, and tests. Moreover, practicing organic chemists have become more reliant on spectroscopic techniques for determination of structures as these techniques have become both more convenient and more accurate. The structural identification of supermolecules with hundreds of atoms has rendered the molecular formula meaningless when talking about these molecules. The use of representations has led to the emergence of research investigations into students’ understanding and use of representations.

To further understand the 1440 organic chemistry exam items, the percentage of exam items using one or more representations in the prompt or answer options were recorded for each exam and this analysis is presented in Figure 3. Across the 18 evaluated exams, items including representations have increased in number. Since 1982, more than 90% of exam items involve representations; this is confirming evidence for the integration of representations into the curriculum and the necessity for students to master representational competence to be successful in organic chemistry. The most common form of representation on organic exams is a molecular line drawing.

Content

Content coverage of any ACS Exam represents a key question for those who are considering whether or not to use the exam. In the case of organic chemistry, the Institute publishes an Organic Chemistry Study Guide, edited by former examination committee members, that provides sample exam items in broad content categories that is meant to cover the topic areas on any current Organic Chemistry Exam. Thus, the chapter titles of the study guide could be used as an initial framework for
categorizing the exams items; additional content areas were added to address exam items that did not fall into the study guide categories. (Content areas from the study guide are indicated in Table 1.) Additionally, many questions were deemed to cover more than one topic; therefore, some exam items were reported in multiple topic areas and thus column totals may add up to more than 100%. Table 1 summarizes the percentage of exam items for each of the exams for 21 content areas so identified.

The percentage of content coverage for the identified areas has varied across time. Some content areas (e.g., biochemistry) have not been covered on all exams. And some content areas have consistently been covered on exams (e.g., substitution and elimination). A notable shift in content coverage can be observed by comparing the percentage of exam items covering qualitative analysis with those covering spectroscopy content (see Figure 4). Qualitative analyses predated spectroscopic methods as a technique for determining structural information (e.g., iodoform test for methyl ketones). The first spectroscopy-related exam item appeared in 1968; the last qualitative analysis exam item appeared in 1991. Much of the chemistry involved in qualitative analysis still appears on the current exams; however, exam items covering that chemistry do not have the intent of measuring student ability to use the chemistry to determine structural features. These exam items now focus on the synthetic applications of the chemistry.

In addition to summarizing the general content coverage over time, Table 1 also provides a lens into how grassroots exam development can be influenced by the work it follows. While one feature of the content coverage is that it has been generally stable, there are small fluctuations on top of this overall stability. When the fluctuations become more noticeable, there is often a correcting action in the subsequent exam. For example, the 2004 exam had an upward fluctuation of 9% with stereochemistry content—up 50% from the relatively stable value of 6% per exam on several previous exams. The 2008 exam then moved lower than the putative common value, including only 4% with stereochemistry. Thus, when a specific exam seems to have too few or too many items on a particular topic, the next committee, which acts as a de novo body, has a tendency to strongly compensate, at least for topics that remain in the curriculum.

Percentile Rankings

Student performance on an ACS exam can be considered in two related ways. The first is the raw score that can be reported as a percentage of the questions answered correctly. The second is a normed reference score. Normed scores are established shortly after the release of the examination based on qualitative analysis with those covering spectroscopy content (see Figure 4). Qualitative analyses predated spectroscopic methods as a technique for determining structural information (e.g., iodoform test for methyl ketones). The first spectroscopy-related exam item appeared in 1968; the last qualitative analysis exam item appeared in 1991. Much of the chemistry involved in qualitative analysis still appears on the current exams; however, exam items covering that chemistry do not have the intent of measuring student ability to use the chemistry to determine structural features. These exam items now focus on the synthetic applications of the chemistry.

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Table 1. Comparison of Percentage of Exam Items by Content Area over Time

<table>
<thead>
<tr>
<th>Content Areas</th>
<th>Items, %</th>
<th>Exams in the 1900s</th>
<th>Exams in the 2000s</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>49</td>
<td>53</td>
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<td>Acids and bases</td>
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<td>2</td>
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<tr>
<td>Addition to pi-bonds</td>
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<td>4</td>
<td>3</td>
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<tr>
<td>Applications</td>
<td></td>
<td>6</td>
<td>5</td>
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<td>Biochemistry</td>
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<td>1</td>
<td>1</td>
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<tr>
<td>Carbonyls: Addition</td>
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<td>2</td>
</tr>
<tr>
<td>Carbonyls: Substitution</td>
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<td>8</td>
</tr>
<tr>
<td>Electrophilic aromatic substitution</td>
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<td>8</td>
<td>12</td>
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<td>Enols and enolates</td>
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<td>2</td>
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<tr>
<td>Nomenclature</td>
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<td>5</td>
<td>6</td>
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<td>Properties</td>
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<td>8</td>
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<tr>
<td>Radical reactions</td>
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<tr>
<td>Redox reactions</td>
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<td>12</td>
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<td>Qualitative analysis</td>
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<td>13</td>
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<td>Substitution and elimination</td>
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<tr>
<td>Synthesis</td>
<td></td>
<td>1</td>
<td>2</td>
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</table>

*aColumn totals may not add to 100%. Some exam items cover more than one content area. *bDenotes study guide chapters.
data from student performances over multiple schools representing a spectrum of institution types and student abilities. Importantly, score return is voluntary, but instructors who return them attest that the test conditions used meet published expectations for factors such as length of time and availability of resources such as calculators. Percentile rankings are provided for every raw score and a table is provided to an instructor who purchases an ACS exam that correlates a given raw score with a particular percentile ranking. Instructors can use percentile rankings to make comparisons of their student performance to the nationally normed sample.

Looking at the raw scores necessary to receive particular percentile rankings across examinations provides a possible metric for understanding the relative difficulty of an examination and the ability of examinations to differentiate between high and low performers. A quick way to visualize this structure of exams is to graph the raw scores (in percentages) necessary to receive a 35th, 50th, 65th, and 80th percentile ranking on exams over time, as shown in Figure 5. The relative raw scores necessary, for example, receiving the 80th percentile ranking is a measure of relative difficulty between the examinations. From 1949 until 1971, the raw scores necessary to receive a given percentile ranking generally decreased; this suggests that the difficulty of the examinations were increasing during this 22-year time period. In 1974 there was a break in this trend, and a marked increase in raw scores is apparent. For example, almost a 20% increase occurred for the 80th percentile ranking. Since 1974, the average raw score necessary to receive an 80th percentile ranking was just below 70%; whereas in the period from 1949 until 1971, the average raw score necessary to receive the same percentile ranking was approximately 60%. As with the other analyses, these data point toward a change in the 1970s regarding the nature of the organic chemistry curricula. One final observation about this figure is that the range of percentiles has not changed dramatically. This result suggests that the process used by ACS Exams’ produces instruments that accomplish the key objective of a norm-referenced exam. Specifically, even when the mean raw score changed dramatically, the spread of student performances was more consistent, and thus the norm-referenced percentiles provide a consistent way to compare students nationally.

CONCLUSION

Through the evaluation and analysis of ACS Organic Chemistry Examinations, it is apparent that organic chemistry exam items for at least the past 30 years are mainly conceptual problems that include one or more representations. Content coverage fluctuates somewhat on different exams, but within a rather modest range. Some content areas do not always appear (or have disappeared across the years) and some content areas consistently appear on the exams. Finally, the average raw score necessary to score in the 80th percentile has been approximately 70% for the past 40 years; this is almost 10% higher than the first 24 years of organic chemistry exams.
In each of these analyses, the 1970s served as a point of inflection where a change was observed (e.g., percentile rankings) or a plateau of change was achieved (e.g., algorithmic, recall, conceptual problem types). Such an observation suggests the question: What was the impetus for such an inflection point? How did the organic chemistry curricula come to reach this equilibrium and what was the reason for the equilibrium prior to 1970? What was the motivation behind the Society Committee on Education publishing a standardized organic chemistry curriculum? Data from ACS exams cannot answer these questions, but the observation does suggest that this time frame may prove fruitful as an era to investigate the historical development of organic chemistry curricula and college chemistry education. At present there has been considerable discussion engendered by proposed changes in the MCAT, and the possible effect these changes could have on the teaching of chemistry courses taken by premed students.19-22 Those who are actively considering curricular responses to this possible external perturbation on the content may find interesting precedents in records of discussions held in this time period, for example.

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■ REFERENCES