Benchmarking problems used in second year level organic chemistry instruction

Jeffrey R. Raker and Marcy H. Towns

Received 21st July 2009, Accepted 10th November 2009
DOI: 10.1039/C001043J

Investigations of the problem types used in college-level general chemistry examinations have been reported in this Journal and were first reported in the *Journal of Chemical Education* in 1924. This study extends the findings from general chemistry to the problems of four college-level organic chemistry courses. Three problem typologies were used as lenses for evaluating the instructional problems. Results of this study include frequency of problem types and comparisons drawn between results in organic chemistry and those in general chemistry. Most notably, a higher percentage of conceptual problems were found in organic chemistry than reported for general chemistry. Implications for use of problem typologies in benchmarking curricular materials are discussed.

Keywords: Organic chemistry, problem types, chemistry education research

Introduction

The development of students' problem-solving abilities is a frequently cited and fundamental objective of the chemistry and broader educational curriculum (*e.g.* Zoller, 1987; Heyworth, 1999; Society Committee on Education, 2003; American Chemical Society, 2008). Several educational researchers have developed problem-solving models in an attempt to understand the process of problem solving and improve problem-solving instruction (*e.g.* Polya, 1957; Fryer and Thomas, 1979; Wheatley, 1984; Hayes, 1989; Tsaparlis and Angelopoulos, 2000). These models have been modified and extended into the field of organic chemistry (Ferguson, 1955; Bowen, 1988; Calimsiz, 2003; Cartrette, 2003; Bhattacharyya, 2004). Other problem-solving researchers have presented problem classification systems (*e.g.* Jonassen, 2003) as a means to further parse out and understand problem solving. While these classification models have been applied to general chemistry courses (such as Bennett J. *et al.*, 2001; Bennett S. W., 2004; Bretz *et al.*, 2004), the utility of these models in organic chemistry has not been fully explored.

We outline the classification of problems used in four second year level organic chemistry courses, describe example problems for each of the classification models, and note any necessary adjustments to those models. Several comparisons are drawn between the organic chemistry and general chemistry results. Finally, we describe how the classification models can be used to understand the second year level organic chemistry curriculum and to benchmark curricular materials.

Classification models

The first edition of the *Journal of Chemical Education* included an article that explored the problem types used in general chemistry final exams at twenty-two colleges and universities (Cornog and Colbert, 1924). The use of the algorithmic, conceptual and recall problem typology has since been used to understand the general chemistry curriculum, assessment practices, and student performance (*e.g.* Nurrenburn and Pickering, 1987). Johnstone (1993) developed a problem typology that has been used to describe general chemistry problems. In our research, we have found another problem typology (Jonassen, 2003) that has not been used to classify assessment problems, but one that we believe merits review. Each model will be discussed in further detail utilizing example problems developed by the authors (JRR and MHT).

Algorithm, conceptual and recall problems

Algorithm and conceptual problems have long been a focus of research and discussion on chemical problem solving in general (or first year) chemistry courses. Nurrenbern and Pickering (1987) asked if there was a difference between performance on algorithmic and conceptual problems. They found that general chemistry students were more successful at algorithmic questions than at conceptual questions. Nurrenbern and Pickering's study revealed that the goals of algorithmic problems are different from those of conceptual problems, and that success in solving one type of problem does not ensure success in solving the other type. Gabel and Bunce (1994) and Phelps (1996) have reported similar results.

Pickering (1990) returned to the impact of conceptual problem-solving success in general chemistry. He found no correlation between success with conceptual questions in general chemistry and the student's overall success in organic chemistry. Nahkleh, Lowrey, and Mitchell (1996) examined the disparity between success in solving algorithm and conceptual questions, and sought to reduce the performance gap. Their study revealed that intentional inclusion of conceptual questions throughout a course *"can improve students' abilities to work successfully with both concepts and*

Department of Chemistry, Purdue University, 560 Oval Drive, West Lafayette, IN 47907-2084, USA. E-mail: mtowns@purdue.edu

algorithms" (p. 762). Thus, there is benefit in extending the algorithm versus conceptual question discussion into the organic chemistry curriculum. To do so, an algorithm versus conceptual question classification system must be established for organic chemistry problems.

Robinson and Nurrenbern (n.d.) have provided guidelines for classifying general chemistry problem types. In addition to algorithmic and conceptual questions, they define a third category: recall questions. Recall questions require fact as the answer. This could include answering a question with a definition, equation, or explanation. The key to recall questions is that the answer is immediately available and no procedure or application of the fact is necessary. For organic chemistry an example would be asking students to name three carbonyl-containing molecules. Algorithmic questions require students to utilize a stepwise procedure to obtain a desired answer. Organic compound nomenclature is often taught and assessed in an algorithmic manner. Likewise, determining stereocenters involves an algorithmic process of labeling and orienting substituent priorities to determine the *R* or *S* assignment. Conceptual questions may necessitate a student to navigate an unfamiliar chemical context (Robinson and Nurrenbern). These questions require a solver to *"justify 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"* (Robinson and Nurrenbern). Typical conceptual organic chemistry problems are to predict the product(s) of a reaction, given a starting material and set of reagents, develop a multistep synthetic scheme to make 'X' molecule from simpler starting materials, and propose a mechanism for a reaction.

Johnstone's classification of problems

Johnstone's (1993) classification of problems is based on the inclusion of data, familiarity of method, and clarity of goals for a given problem. As Johnstone wrote:

> *They [problems] can be thought of as having three parts: some starting information, a goal or desired outcome, and a method of getting from where we are to where we want to be. If one or more of these components is missing or incomplete or fuzzy, we have a problem.* (2001, p. 69)

This model includes eight categories of problems as shown in Table 1.

A type 1 problem is described as having the data given, method familiar, and output given. For example in organic chemistry, the question draw '(*S*)-4,4-dimethyl-2-pentanol' would be an example of a type 1 problem. The IUPAC name provides sufficient information to draw the compound, a method of converting name to structure is a key aspect of organic chemistry instruction, and the goal of drawing the compound is clearly stated. Mechanistic problems used in organic chemistry are examples of type 2 problems. The starting material, product, and reaction conditions are clearly defined. The method to convert the starting material to product is not so apparent. This is the result of a known mechanism being applied to a new chemical context. Wood (2006) stated that the instructional goal of type 2 problems is

Table 1 Johnstone's (1993) classification of problems

Type	Data	Method	Output
1	Given	Familiar	Given
2	Given	Unfamiliar	Given
3	Incomplete	Familiar	Given
4	Incomplete	Unfamiliar	Given
5	Given	Familiar	Open
6	Given	Unfamiliar	Open
7	Incomplete	Familiar	Open
8	Incomplete	Unfamiliar	Open

Table 2 Jonassen's (2003) typology of problem solving

Logical
Algorithm
Story problem
Rule-using problem
Decision making
Trouble-shooting
Diagnosis-solution
Designs
Case analysis
Dilemmas
Strategic performance

to *"look for parallels to known methods"* (p. 99). Multi-step syntheses are type 4 problems. The goal, the product, is clearly defined. However, the data is often presented as guidelines such as *"use any organic molecules with four or fewer carbons, and any necessary inorganic reagents"* and not a specific starting material. Similarly, the method, the multiple steps necessary to synthesize the compound, are not always directly accessible. Type 1, 2, and 4 problems are in stark contrast to type 8 problems, which parallel the research experience, where a decision has to be made about what to research, a procedure developed, more data have to be collected, and a decision made about how to represent conclusions.

Jonassen's (2003) typology of problem solving

Jonassen's (2003) typology extends beyond the three-parameter and eight-category classification system of Johnstone. Jonassen (2003) identified eleven problem types, as shown in Table 2.

Logical problems are puzzle-oriented, requiring efficient manipulations within an abstract task; an example from organic chemistry would be to draw all the constitutional isomers with the molecular formula, C_4H_8.

Algorithmic problems are similar to the algorithmic problems previously defined in the Algorithm/Conceptual/Recall model; however, story problems are considered a separate problem type. Both *algorithmic* and *story problems* in the Jonassen typology require the application of an algorithm to obtain a solution; story problems, though, have shrouded variables within a given context. For example, Fig. 1 poses the problem of calculating the enthalpy change for a given reaction.

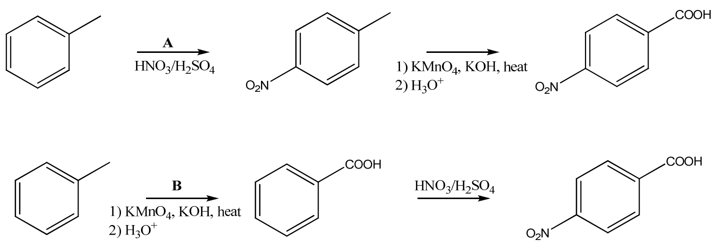
This **story problem** requires a solver to sort through the data provided and determine which is appropriate in conducting the calculation.

Given the bond dissociation energies below (in kcal/mol), estimate the $\Delta_r H^o$ for one of the propagation steps of the radical bromination reaction:

$$(CH_3)_3C\cdot + Br_2 \rightarrow (CH_3)_3CBr + Br\cdot$$

$(CH_3)_2CH$-H: 95	$(CH_3)_3C$-H: 91
$(CH_3)_2CH$-Br: 68	$(CH_3)_3C$-Br: 65
Br-Br: 46	H-Br: 88

Fig. 1 An example of a story problem.



Scheme 1 An example of a decision-making problem.

Rule-using problems are the first of the conceptual problems in this model, where concepts are applied to chemical systems to construct solutions. The concepts (or rules, as defined by Jonassen) constrain the possible answers. Take the following problem: 'which compound, 2-methyl-2-propanol or 1-butanol, has a higher boiling point?' A student would need to determine what concepts related to boiling point are relevant to the given compounds before selecting a final answer.

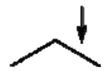
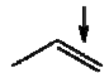
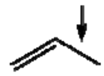
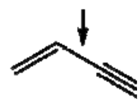
Jonassen (2000) defined **decision-making problems** as those problems that *"typically involve selecting a single option from a set of alternatives based on a set of criteria"* (p. 77). Again from organic chemistry, an example would be when presented with two potential synthetic pathways, a decision must be made as to which pathway to attempt experimentally (see Scheme 1).

This is an example of a classic problem of substituent effects in electrophilic aromatic substitution. By following path **A**, the methyl group directs a *para*-substitution pattern, after which the methyl group can be easily oxidized to the carboxylic acid. By following path **B**, the oxidation of the methyl group initially creates a *meta* directing group, and thus nitration is highly unlikely to occur at the *para* position. Thus path **A** is the correct choice for producing *p*-nitro-benzoic acid.

Let us assume that path **B** was chosen to make the *para*-substituted product. Spectroscopic analysis could be used to determine that only the meta-substituted product was formed. A **troubleshooting problem** has thus emerged. Why was the *para*-substituted product not formed? The process of generating an answer to this question involves troubleshooting.

After understanding why the desired product was not formed via path **B**, a **diagnosis-solution problem** often follows. *"Now that I understand why path **B** did not work, how can I form the desired para-substituted product?"* Once again, an understanding of the importance of sequence in electrophilic aromatic substitution will assist in proposing a viable solution, *e.g.* proposing path **A**. Three problem types

Table 3 Carbon-carbon bond lengths in a series of compounds

	1.53 Å		1.48 Å
	1.51 Å		1.38 Å
	1.47 Å		1.43 Å

have thus emerged from one problem prompt (*decision-making*, *troubleshooting*, and *diagnosis-solution*).

Evaluation of the two proposed pathways for the purpose of choosing an appropriate experimental pathway is an example of a *decision-making problem*. Only after having conducted the incorrect path **B** does the (*trouble-shooting*) problem materialize, namely the understanding why the path did not work. *Diagnosis-solution problems* often proceed from trouble-shooting; now that it is understood why the path did not work, an alternative solution can be proposed. A decision-making problem is a choice between two or more options. A trouble-shooting problem attempts to answer why something has occurred. A diagnosis-solution problem proposes a solution to a problem.

Design problems are the most commonplace problems in the organic chemistry curriculum. A target molecule is retrosynthesized to available starting materials. A pathway is then determined for the generation of the target molecule. Solutions to design problems are constrained by the problem solver's knowledge of reactivity, specific reactions, and available starting materials.

Case analysis problems can best be understood in the context of many problem-based learning activities. Take for example, Table 3. This table contains bond length data for a series of compounds. Students would be asked to explore the variations between the given bond lengths. General relationship, such as the hybridization of participant atoms in the bond, electronegativity of participant atoms in the bond, resonance effects or inductive effects can emerge as solutions. Case analysis problems can be experimental or instructional. In the instructional setting, students are guided to the problem solution, whereas in the experimental setting, a chemist is developing a theory or model (*i.e.* a solution) to the given case of data.

Dilemma-type problems are difficult to describe in the context of second year level organic chemistry. The chemistry classroom has not traditionally been an environment for discussions of personal, social, and ethical dilemmas. Chemical carcinogenicity of reagents, fatal diastereomers of drugs and other such examples are presented in the classroom; however, problems where a student must propose, for example, organic chemistry relevant solutions to global warming, are not common in second year level instruction.

Up to this point, each problem has been posed in a non-dynamic problem-solving environment (*e.g.* quizzes or examinations). Problems can and do emerge in the context of some action and must be solved under time constraints. Take for example driving a car: a large boulder rolls into the middle of the road. At this point a driver does not have the option to generate all possible solutions, time to look-up in the literature how others have solved this problem, and/or time to consult with their research advisor as to an appropriate line of action. There is a finite amount of time for action after the problem emerges. Jonassen labels these problems as **strategic performance problems**.

Even in the teaching laboratory, students attempt to conduct organic chemistry in a controlled environment. And yet *strategic performance problems* emerge. Evidence is in the form of productivity. The initial task is to synthesize a compound during two 3-hour laboratory periods. A host of inhibitors to this task can arise: mishandling and loss of product or starting material, lack of necessary equipment or reagents, or mislabeled reagents. The task remains the same and yet inhibitors to completion arise in unpredictable dynamic systems.

The Algorithm, Conceptual, and Recall classification, Johnstone's (1993) Classification of Problems, and Jonassen's (2003) Typology of Problem Solving provide three distinct theoretical lenses by which to view problems posed in organic chemistry instruction. The next section will describe how these three lenses were used to evaluate second year level organic chemistry problems.

Methodology

Homework assignments, quizzes, and examinations were obtained for four semester-long second year level organic chemistry courses at a large Midwestern research university. These courses represent the first and second semester of two year-long organic chemistry tracks. One track is designed for science and chemical engineering majors, the other is populated with agricultural and health science majors. A total of 792 individual problems were obtained for the four courses; the course professors wrote all of the problems. Problems were coded according to the three problem typologies.

Inter-rater reliability

Inter-rater reliability was established by two reviewers evaluating a sample of problems (n = 36) representing a diverse set from the three problem typology models. One reviewer evaluated the problems using the Jonassen model, while the other reviewer evaluated the problems using the Johnstone and the Algorithm/Conceptual/Recall models. An initial percent agreement was calculated: Algorithm/Conceptual/Recall, 62.5%; Johnstone, 81.3%; Jonassen, 78.1%. Both reviewers met individually with JRR to discuss their evaluation. Following the discussion, a final percent agreement was calculated: Algorithm/Conceptual/Recall, 84.4%; Johnstone, 81.3%; Jonassen, 90.6%.

The following are three examples of unresolved disagreements with our raters. An example of a disagreement between raters for the algorithm, conceptual, and recall typology is this, "*Explain how **P** is consistent with the spectral data.*" Our rater classified spectral confirmation as an algorithmic process of matching observed peaks with molecular features (*e.g.* functional groups). We believe this type of problem is conceptual in nature because a synthesis of data is necessary to confirm the given structure with the spectral data.

This same problem was cause for disagreement with the Jonassen (2003) typology. Our rater classified the problem as a diagnosis solution problem. We maintain that spectral confirmation problems are trouble shooting problems where the answer is derived from a set of hypotheses and confirmations.

The debate on the Johnstone problem classification was based on the three characteristics of data, method, and goal. For example, we disagreed on whether the data was complete or incomplete for the problem, "*Given that secondary H's are 4.5 times as reactive as primary H's, predict the percentage of each monochlorinated product of n-butane + chlorine.*" We ultimately decided that the data for this problem was complete.

After discussions with the reviewers, JRR augmented the Johnstone and Jonassen models to include a 'recall' category. Neither model acknowledged 'recall' questions and none of the available problem categories in either model fit 'recall' questions. For example, questions like 'why were Friedel-Crafts reactions invented?' or 'how many valence electrons are there around the charged carbon in an alkyl anion (*n*-butyl anion, for example)?' are not classifiable using the Johnstone or Jonassen models. As with the Johnstone model, questions of recall type do not classify according to data completeness, method clarity, or output clarity. The entire problem set (n = 792) was then coded or recoded using the augmented models.

Results

We have thus focused our results for the three problem typologies on examination and final examination problems. Examination questions (34% of sample) are highly representative of the type of material a student is expected to learn throughout a course, and the types of problems a student is expected to be able to solve. Cornog and Colbert (1924) choose to focus their problem evaluation on final examination questions for this very reason:

> "*It seems probable that the content of final examination questions express more certainly than information from any other source just what ideas constitute the irreducible minimum of chemical knowledge a student must posses to pass the course.*" (p. 9)

The focus on exam and final exam questions is reiterated in the work of Bretz, Smith, and Nahkleh (2004) and Bennett (2004, 2008). Our results reflect the focus on examination questions in the literature.

The simplest of the problem typologies is the algorithm, conceptual, and recall classification system (see Table 4). As early as 1924, chemical educators have used this system to understand instructional materials (Cornog and Colbert). As shown in Table 4, conceptual problems represented 72% of all exam and final exam questions. When only final exam questions were considered, 82% were conceptual in nature.

Table 4 Percentage of problems by the algorithmic/conceptual/recall classification

	Exam and final exam (n = 479)	Final exam (n = 211)	General chemistry final exam questions (Cornog and Colbert, 1924, p. 8; n = 1834)	General chemistry (1^{st} term) exams (Bretz *et al*., 2004; n = 40)	General chemistry (2^{nd} term) exams (Bretz *et al*., 2004; n = 40)
Conceptual	72	82	23.5	53	46
Algorithm	20	9	36.2	23	16
Recall	8	9	26.3	24	38

Data from this study have been shaded. Column sums may exceed 100% due to rounding.

Rather than memorize a litany of chemical facts, organic chemistry students were required to retrieve concepts, connect them in meaningful ways, and apply those concepts to the problem. Conceptual problems included predicting products for reactions, and explaining how to differentiate two compounds using proton NMR spectra. Algorithm problems (20% of the exam and final exam questions) represented a noteworthy portion of questions. These problems included *"draw structures of all alkenes with the molecular formula* C_4H_8*."* Recall type problems were hardly used on examinations. Our evaluation of problem types used in organic chemistry had a marked difference from those presented in general chemistry: organic chemistry problems were strongly focused on conceptual problems.

Cornog and Colbert (1924) used this typology to classify final exam questions from general chemistry courses and found that general chemistry questions were spread across the three categories of algorithm, conceptual, and recall questions. Their study also included a fourth problem type entitled 'useful applications' representing 13.8% of the general chemistry problems; using minimal descriptions of this category in their manuscript, it was determined that this category did not accurately describe algorithmic, conceptual, or recall questions.

Bretz, Smith, and Nakhleh (2004) categorized problems given on the General Chemistry (1^{st} and 2^{nd} Term) – 1997 Special Edition American Chemical Society Exams. Unlike the distribution of problem types in the Cornog and Colbert (1924) categorization, Bretz *et al*. found a strong emphasis on conceptual questions. This difference can be attributed to the focus conceptual problems have received in the chemical education literature over the past 80 years (*e.g.* Nurrenburn and Pickering, 1987). Given the 'national' perspective of ACS Exams, a significant number of conceptual problems would be expected to be included. The 2^{nd} term exam has a higher percentage of recall questions (38%) than the 1^{st} term exam.

Comparing the Cornog and Colbert (1924); Bretz, Smith, and Nahkleh (2004); and our data, the distinction between general and organic chemistry is clear. The transition of a student from general to organic chemistry is a transition that includes changing assessment expectations. Knowledge in organic chemistry is not primarily assessed through algorithmic or recall means, but through conceptual means.

The difference between general and organic chemistry problems is not as pronounced when using the lens of Johnstone's (1993) classification of problems. The first two columns of Table 5 display the results of our study on organic chemistry problems. Type 0 (Recall), 1, and 2 problems encompass 99% of the problems. These problems included labeling each asymmetric carbon in the given examples as R or S (type 1 problem) and *"provide a mechanism for the observed product"* (type 2 problem, method unfamiliar). The remaining three columns present the results of two studies by S.W. Bennett (2004, 2008). Similarly, 90% or more of problems are described as Type 1 or 2. Bennett's studies do not include a Type 0 problem as will be described below.

Table 5 Percentage of problems by Johnstone's (1993) classification of problems

	Exam and Final Exam (n = 479)	Final Exam (n = 211)	Exams (Bennett, 2004)	1^{st} Year Exams (Bennett, 2008)	3^{rd} Year Exams (Bennett, 2008)
0 (Recall)	8	9	–	–	–
1	86	83	95	94	90
2	6	8	3	3	4
3	0	0	2	3	4
4	<1	<1	0	0	2
5	0	0	<1	<1	1
6	0	0	0	0	0
7	0	0	0	0	0
8	0	0	0	0	0

Data from this study have been shaded. Column sums may exceed 100% due to rounding.

Bennett in 2004 and 2008 reviewed chemistry exam questions from several universities in Australia, the United Kingdom, and the United States. In both years and despite separating first and third year exam questions, the same pattern of problem type percentages emerged. Over 90% of questions evaluated in Bennett's studies represent type one problems, where data, method, and output were explicitly given. Our evaluation of organic chemistry exam questions mirrors Bennett's trends. However, in establishing the inter-rater reliability it emerged that recall questions as determined in the algorithm, conceptual, and recall typology were not adequately represented in Johnstone's model. Recall questions cannot be evaluated according to whether data, method, and outputs were clear. We have reported a type zero problem category in Table 5 to note the subset of problems that do not fit within the Johnstone model. It cannot be accurately determined how Bennett addressed recall type questions. However, in this study, if type zero problems were merged with type one problems, these results would highly resemble those of Bennett's problem type one results.

We have been unable to locate the use of Jonassen's (2003) typology of problem solving to evaluate instructional problems in chemistry or any academic field. Jonassen reported the purpose of his model to generate and develop instructional problems; we, however, have used the model as an evaluative measure of problem use in organic chemistry instruction.

Our problems were classified into seven of the problem type categories (*rule-using*, *algorithm*, *recall*, *trouble-shooting*, *diagnosis*, *story*, and *design*). By visual inspection, a similar distribution of the problems across the seven observed types exists between all examination questions, final examination questions, and all problems. We did not locate examples of five of Jonassen's eleven problem types (*case analysis*, *decision-making*, *dilemmas*, *logical*, and *strategic performance*) in this study. During the inter-rater reliability study, we discussed the problem types that were not found in the sample set. While such problems could be constructed, we did not find evidence of their use in assessment in this data set.

Similarly to Johnstone's model, it was determined that recall problems do not fit into the Jonassen typology. Table 6 thus reflects twelve problem types, Jonassen's original eleven and a recall problem classification.

Percentages of all problems evaluated have been included in Table 6. The data demonstrate that percentages of all exam questions and the entire sample set of problems are relatively similar.

The majority of problems represent *rule-using problems*, a type of conceptual problem where concepts are applied to chemical systems to construct solutions. An example question from our data is: *"draw the two chair conformations of the following compounds. Circle the most stable one (or both if they are isoenergetic) and calculate their energy difference"* (*rule-using problem*). Other problem types found included *"starting from benzene and any reagents you choose, devise a synthesis for p-chlorostyrene"* (*design problem*) and *"when (trans)-1-bromo-2-methylcyclohexane is heated in ethanol, four different products are formed. What condition would change the outcome of this reaction by promoting the production of 3-methylhexane as the major product"* (*diagnosis solution problem*).

Table 6 Percentage of problems by Jonassen's (2003) typology of problem solving

	Exam and final exam (n = 479)	Final exam (n = 211)	All problems (n = 792)
Rule-using	62	70	61
Algorithm	18	6	17
Recall	8	9	7
Trouble-shooting	6	8	7
Diagnosis	4	4	5
Story	3	3	3
Designs	1	<1	1
Case analysis	0	0	0
Decision making	0	0	0
Dilemmas	0	0	0
Logical	0	0	0
Strategic performance	0	0	0

Column sums may exceed 100% due to rounding.

Discussion

Our study found a stronger emphasis on conceptual problems in organic chemistry instruction in comparison to studies of problems in general chemistry instruction using the algorithmic, conceptual, recall model. The recall questions from this model were thus categorized with the other two models. Algorithmic and conceptual problems were not distinguishable on the Johnstone (1993) model. Jonassen defined two categories of algorithmic problems into algorithmic and story problems. The remainder of the problems with the Jonassen model were conceptual problems. Our organic chemistry results were similar to those in general chemistry using the Johnstone classification of problems. As with general chemistry, the majority of organic chemistry problems were localized in the Type 0, 1, and 2 categories. This model could serve as a curricular design tool when composing new instructional problems. Lastly, we found a preponderance of organic chemistry problems classified as *rule-using* with the Jonassen (2003) Model. *Case analysis* is one problem type that was not found, but that could easily be used as an instructional problem in organic chemistry.

The three models and results presented have implications for organic chemistry instructors: the structure of learning objectives, the curriculum, and assessments in the course. If the instructor has determined learning objectives in the course, then homework, quiz, and exam problems can be written or chosen in alignment with those objectives. The models provide a lens by which instructors can ensure that homework, quizzes, and exams have varied amounts of problem types. These classification models also provide a method to monitor the types of problems that are assigned. The models can be used to ensure that students have developed the ability to respond to different types of problems before they are faced with them on an exam.

Each model provides a unique utility for organizing and differentiating problems. The algorithm, conceptual, and recall model is a quick way to balance an exam. Our data showed a preponderance of type 0 (recall) and type 1 problems using the Johnstone (1993) model. This does not provide much differentiation, given current assessment practices. The Johnstone model could provide a lens for constructing new instructional problems. The Jonassen (2003) typology provided the largest differentiation of problem types (7) with a strong tendency towards 'rule-using' problems. Five problem types in the Jonassen's typology were not found in our sample, and thus the typology could provide another lens for instructional material development.

The results also serve as an initial benchmark for more holistic evaluations of organic chemistry instruction. The reported benchmark can serve as comparisons to other chemistry courses preceding and succeeding organic chemistry, between chemistry departments, national chemistry curricular goals, and for inclusion in university accreditation documents.

We have demonstrated the utility of the three problem typologies for evaluating problems used in organic chemistry instruction. Appropriate references to the use of the models to evaluate general chemistry instruction have been used to provide a comparison to courses beyond organic chemistry. Each chemistry discipline (*e.g.* physical chemistry or biochemistry) could utilize these models for content-specific description of their instructional problems. At the departmental level, results of a comprehensive evaluation of instruction across all undergraduate chemistry courses could inform understanding of varied success with the diverse educational objectives within the chemistry curriculum. Data of this nature would be valuable for establishing reform goals on both a local (departmental) and national level.

The American Chemical Society Examinations Institute has provided assessment tools for benchmarking student performance since 1930. Two such exams were discussed in this manuscript (Bretz, Smith, and Nakhleh, 2004). No single benchmarking tool or repository exists for the study of curricular materials. Departments wishing to justify a change in curricular goals to a more diverse problem-based curriculum have no reference point for making such an argument. Bruck, Bretz, and Towns (2008) described a similar goal and justification for a tool to assess the level of inquiry in the undergraduate laboratory. The data presented herein can begin as a source for such comparisons that must be expanded to include additional institutions and chemistry courses for such a broad-based benchmark to be effective.

Student learning and effective teaching are cornerstone goals for university accreditation (*e.g*. The Higher Learning Commission, 2003). Diverse and innovative curricular materials are evidence for fulfilling such goals. Our utilization of problem typologies can be used as a tool for describing current instructional materials and for describing a diversification of instructional materials. Comparative data of curricular tools to peer institutions can inform the success of an institution's instruction.

Conclusion

The purpose of this problem type assessment was to demonstrate the utility of the three theoretical models for evaluating and to establish a benchmark for developing new instructional materials. The Johnstone (1993) and Jonassen (2003) models were modified to include recall type problems into their models. Organic chemistry problems are predominately conceptually based and provide sufficient data, methods, and directed outputs for the problem solver. Our utilization of the typologies can have multiple uses in assessing current and establishing future curricular practices.

Acknowledgements

We would like to thank especially the three professors who supplied the problem sets used as data in this study. We would also like to thank Mr. Aaron Bruck and Ms. Nicole Becker, members of the Towns Research Group, for assisting with determining inter-rater reliability. Lastly, we would like to thank Dr. Nathan Grove, Clemson University, for his thoughtful review of this article and suggestions for improvement.

References

American Chemical Society, (2008), *Undergraduate professional education in chemistry: ACS guidelines and evaluation procedures for bachelor's degree programs*, Washington, D.C.: American Chemical Society.

Bennett J., Rollnick M., Green, G. and White M., (2001), The development and use of an instrument to assess students' attitude to the study of chemistry, *Int. J. Sci. Educ*., **23**, 833-845.

Bennett S. W., (2004), Assessment in chemistry and the role of examinations, *Univ. Chem. Educ*., **8**, 52-57.

Bennett S. W., (2008), Problem solving: can anybody do it? *Chem. Educ. Res. Pract*., **9**, 60-64.

Bhattacharyya G., (2004), *A recovering organic chemist's attempts at self-realization: how students learn to solve organic synthesis problems*, Purdue University, West Lafayette, IN.

Bowen C. W., (1988), *A qualitative analysis of graduate student problem solving in organic synthesis*, Purdue University, West Lafayette, IN.

Bretz S. L., Smith C. and Nakhleh M. B., (2004), *Analysis of the ACS Blended General Chemistry Exams using a new coding framework*, Paper presented at the 227th American Chemical Society National Meeting.

Bruck, L. B., Bretz, S. L., and Towns, M. H. (2008). Characterizing the level of inquiry in the undergraduate laboratory. *J. Coll. Sci. Teach*., **38**, 52-58.

Calimsiz S., (2003). *How undergraduates solve organic synthesis problems. A problem-solving model approach*, Purdue University, West Lafayette, IN.

Cartrette D. P., (2003), *Using spectral analysis to probe the continuum of problem solving ability among practising organic chemists*, Purdue University, West Lafayette IN.

Cornog J. and Colbert J. C., (1924), What we teach our freshman in chemistry, *J. Chem. Educ*., **1**, 5-12.

Ferguson L. N., (1955), The orientation and mechanism of electrophilic aromatic substitution, *J. Chem. Educ.*, **32,** 42-45.

Fryer M., and Thomas D. A., (1979), *Successful problem solving: a practical guide for the student and professional*, Skokie, IL: National Textbook Company.

Gabel D. L. and Bunce D. M., (1994), Research on problem solving: Chemistry, in D. L. Gabel (Ed.), *Handbook of research on science teaching and learning* (pp. 301-326), New York: Macmillan.

Hayes J., (1989), *The complete problem solver* (2nd ed.), Philadelphia: The Franklin Institute.

Heyworth R. M., (1999), Procedural and conceptual knowledge of expert and novice students for the solving of a basic problem in chemistry, *Int. J. Sci. Educ*., **21**, 195-211.

Higher Learning Commission, The, (2003), H*andbook of accreditation* (3rd ed.), Chicago, IL: The Higher Learning Commission.

Johnstone A. H., (1993), In C. Wood and R. Sleet (Eds.), *Creative problem solving in chemistry*, London: The Royal Society of Chemistry.

Johnstone A. H., (2001), Can problem solving be taught? *Univ. Chem. Educ*., **5**, 69-73.

Jonassen D. H., (2000), Toward a design theory of problem solving, *Educ. Tech. Res. Dev*., **48**(4), 63-85.

Jonassen D. H., (2003), *Learning to solve problems: an instructional design guide*, Hoboken, NJ: Wiley.

Nakhleh M. B., Lowrey K. A. and Mitchell R. C., (1996), Narrowing the gap between concepts and algorithms in freshman chemistry, *J. Chem. Educ.*, **73**, 758-762.

Nurrenbern S. C. and Pickering M., (1987), Concept learning versus problem solving: is there a difference? *J. Chem. Educ*., **64**, 508-510.

Phelps A. J., (1996), Teaching to enhance problem solving, *J. Chem. Educ*., **73**, 301-304.

Pickering M., (1990), Further studies on concept learning versus problem solving, J. Chem. Educ., **67**, 254-255.

Polya G., (1957), *How to solve it: a new aspect of mathematical method*, Princeton, NJ: Princeton University Press.

Robinson W. R. and Nurrenbern S. C., (n.d.), *Conceptual questions (CQs): what are conceptual questions*? Retrieved May 25, 2009, from http://jchemed.chem.wisc.edu/JCEWWW/Features/CQandChP/CQs/WhatAreCQs.html

Society Committee on Education, (2003), *Exploring the molecular vision*: American Chemical Society.

Tsaparlis G. and Angelopoulos V., (2000), A model of problem solving: its operation, validity, and usefulness in the case of organic-synthesis problems, *Sci. Educ*., **84**, 131-153.

Wheatley G. H., (1984), *Problem solving in school mathematics*, West Lafayette, IN: Purdue University, School Mathematics and Science Center.

Wood C., (2006), The development of creative problem solving in chemistry, *Chem. Educ. Res. Pract*., **7**, 96-113.

Zoller U., (1987), The fostering of question-asking capability, *J. Chem. Educ*., **64**, 510-512.