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Measuring Student Performance in General Organic Chemistry

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Student performance in general organic chemistry courses is determined by a wide range of factors including cognitive ability, motivation to cultural capital. Previous work on cognitive factors has tended to focus on specific areas rather than exploring performance across all problem types and cognitive skills. In this study, we have categorized the different kinds of problems encountered in general organic chemistry, and correlated performance in each problem type with overall class performance. Fairly reproducible results are found for ten consecutive semesters over five academic years. Problem types that require higher-level cognitive skills tend to correlate better with overall class performance than those that rely more heavily on memorization. Performance on some problem types was found to predict up to ~90% of the variances of overall class performance. Correlations across problem types with external student characteristics, such as general chemistry grade, are interpreted as highlighting the important contributions of other factors in addition to cognitive ability to success in organic chemistry.

Keywords: Organic Chemistry, Problems, Assessment, Cognition, Motivation

Introduction

The two-semester general organic chemistry course in the U.S. is required for many college students who are not chemistry or biochemistry majors, and is often considered to be one of the more challenging in their undergraduate careers (Grove and Bretz, 2010; Zoller, 2011). Organic chemistry is also described as a roadblock course for pre-health students who wish to enter medical, dental, and other professional schools (Rowe, 1983; Lovecchio and Dundes, 2002; Barr *et al.*, 2010), particularly in underrepresented student populations (Carmichael *et al.*, 1986; Barr *et al.*, 2008). Many approaches to improve student success in organic chemistry have been described in the literature. Examples include curriculum and course content development (Reingold, 2004; Grove *et al.*, 2008; Lopez *et al.*, 2011; Flynn and Biggs, 2012; Raker and Towns, 2012), incorporation of active learning strategies (Paulson, 1999; Muthyala and Wei, 2013), implementation of peer-led team learning (Gosser and Roth, 1998; Tien *et al.*, 2002), the use of in-class technology (Dertin, 2008; Flynn, 2011; Ryan, 2013) and electronic and online homework systems (Dori, 1995; Penn *et al.*, 2000; Chamala, 2006; Chen and Baldi, 2008; Chen *et al.*, 2010; Parker and Loudon, 2013).

Predictors of student performance in organic chemistry have been the subject of several recent studies (see, for example, Szu *et al.*, 2011; Lopez *et al.*, 2014). To completely understand student performance it would be necessary to characterize the relative contributions of three fundamental contributing factors, i.e., cognitive ability (Ausubel *et al.*, 1978), motivation (Deci *et al.*, 1991; Zimmerman and Bandura, 1992) and cultural capital (Bourdieu *et al.*, 1990). A quantitative description of performance in terms of these three factors would represent a challenging long-term research project. Part of the problem is simply quantifying performance. The information content in a final grade or single point total at the end of the semester is rather low, and we wondered if there was a more informative way of describing student performance using simple standard assessments.

Cognitive ability is perhaps the most frequently studied contributing factor in organic

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4 chemistry. Previous work has focused on specific cognitive skills such as the ability to visualize
5 3-dimensional structures (Stieff, 2010; Oke and Alam, 2010; Ferk *et al.*, 2003), specific types of
6 problem solving ability (Cartrett and Bodner, 2010; Ferguson and Bodner, 2008; Bhattacharyya
7 and Bodner, 2005; Kraft *et al.*, 2010), representational models (Bodner and Domin, 2000),
8 thinking patterns (Taagepera and Noori, 2000) and concept development (Nash *et al.*, 2000;
9 Grove *et al.*, 2012). Rather than concentrating on a specific cognitive area, we wondered if a
10 more holistic approach might be useful. For example, nomenclature problems involve mainly
11 the application of memorized rules, and are more relevant to the "Remember" and "Understand"
12 categories of the cognitive domain of the revised Bloom taxonomy (Anderson *et al.*, 2001).
13 Solving complex multi-step synthesis problems, or deriving the mechanism of a reaction that has
14 not previously been seen, however, are more relevant to the "Apply", "Evaluate", and "Create"
15 categories. These latter types of organic chemistry problems test the ability of students to apply
16 existing knowledge in new contexts, consistent with conventional understandings of true
17 problem solving and learning (Bruner, 1960). Students might be expected to perform differently
18 on organic chemistry problems that call on different categories of the cognitive domain, due to
19 divergent cognitive skill sets.

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21 Here, we describe a simultaneous analysis of student performance over the entire range of
22 organic chemistry problem types, and presumably cognitive skills, to obtain a more detailed
23 insight into student performance. The study takes advantage of a large dataset that includes
24 almost 4000 individual student performances collected over five academic years. Problems used
25 in the course examinations were categorized into different types based on conventional organic
26 chemistry topics, and student performance was analyzed by problem type. Reproducible patterns
27 of student performance over the different problem types were observed. Some problem types
28 were found to be highly predictive of overall performance.

Experimental Approach and Collected Data

Student performance data was collected for the general organic chemistry courses offered at a large public institution in the Southwestern United States. The study was assigned exempt status by the institution's IRB. At this institution, general organic chemistry is taught as two separate courses in different, usually consecutive, semesters; the first semester course is taught in fall and the second in spring. Data was collected from the first semester course of fall 2009 through the second semester course of spring 2014, i.e., ten consecutive semesters over five complete academic years, to generate a student performance dataset of 3925 (the number of individual students who participated is lower since some students took both the fall and the spring semester classes). The number of students studied in each semester and their overall mean scores are summarized in Table 1. The mean scores for the various semesters were similar (Table 1), however, an analysis of variance indicated a statistically significant difference across the fall semesters, $F(4, 2047)=5.36, p=.00$, and also across the spring semesters, $F(4, 1868)=24.7, p=.00$. Thus, the overall class performances were similar but not identical over the time period of the study. It is not surprising that small differences are found since although all classes had the same instructor and similar materials, there are inevitable small changes in teaching style, content coverage and diversity in class populations over 5 years.

The first semester course covers basic organic chemistry principles such as bonding and mechanistic concepts, alkane conformations, nomenclature, chirality, spectroscopy, substitution and elimination reactions of alkyl halides, and reactions of alkenes. The second semester course covers the remainder of the standard functional group chemistry, retrosynthetic analysis, and simple pericyclic reactions, but excludes the chemistry of biomolecules or polymers. Students are assessed each semester using three midterm exams and one comprehensive final exam. All examination questions were short answer type, multiple choice was not used. Different graders were used each semester, but all graders generated their grading rubrics in consultation with the class instructor.

Table 1 Numbers of Students, Demographic Data, Their Average Final Course Scores and Corresponding Standard Deviations for all Semesters of Organic Chemistry Included in this Study^a

	First Semester (Fall)					Second Semester (Spring)				
	2009	2010	2011	2012	2013	2010	2011	2012	2013	2014
No. of Students	351	408	402	432	459	344	373	373	367	416
Female (%)	57.0	48.3	46.5	49.3	58.2	56.4	48.0	44.0	43.1	53.1
Male (%)	42.7	51.5	53.5	50.7	41.4	42.7	51.7	56.0	56.7	46.9
White (%)	61.8	60.0	64.2	56.7	54.7	59.9	57.9	63.5	60.5	57.2
Hispanic (%)	17.4	14.0	11.9	16.4	14.4	16.9	15.0	14.2	15.5	12.5
Asian (%)	15.7	17.6	16.4	18.5	22.0	17.2	18.2	15.3	16.1	22.8
Black/African American (%)	0.9	3.4	2.0	2.8	1.1	0.9	2.9	3.2	1.9	1.9
Native American (%)	0.6	1.0	0.5	0.7	0.4	0.3	1.1	0.3	0.8	0.5
Two or More Races (%)	1.1	0.3	3.3	3.7	5.9	1.2	0.5	2.4	4.1	4.3
Avg. Score (%)	67.3	73.9	71.7	69.5	72.4	68.8	74.2	65.6	75.6	73.9
Std. Dev (%)	18.2	15.9	16.9	17.4	16.6	18.3	17.2	17.8	16.1	15.9

^a In cases where gender and demographic data do not sum to 100%, the remainder is not reported.

Table 2 Question Categorization into Problem Types, and the Number of Discriminating Questions per Category by Semester (the Numbers in Parentheses are the Total Number of Questions per Semester, Including Non-Discriminating Ones)

Problem Type	First Semester (Fall)					Second Semester (Spring)					Total
	2009	2010	2011	2012	2013	2010	2011	2012	2013	2014	
Nomenclature (1)	4	2	1	3	2	3	1	4	2	3	25
Bonding/Concepts (2)	8	8	8	10	10	1	1	0	2	1	49
Acidity/Basicity (3)	3	3	2	5	3	4	4	2	3	3	32
Spectroscopy (4)	4	2	6	5	5	2	2	1	0	0	27
Chirality (5)	1	1	1	0	0	--	--	--	--	--	3
Mechanism (6)	18	8	5	5	6	10	11	16	7	9	95
Reagents/Products (7)	14	10	5	3	3	24	20	15	6	14	114
Synthesis (8)	--	--	--	--	--	11	12	9	6	9	47
Pericyclic Reactions (9)	--	--	--	--	--	3	7	3	4	5	22
Conformations (10)	5	4	4	5	5	--	--	--	--	--	23
Total Questions	57 (64)	38 (49)	32 (38)	36 (39)	34 (36)	58 (67)	58 (70)	50 (54)	30 (38)	44 (49)	437 (504)

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4 Each exam question was categorized according to one of ten major problem types as
5 summarized in Table 2. No attempt was made to also categorize the questions in terms of
6 cognitive category for several reasons. First, the main focus of this investigation is to learn how
7 to quantify student performance in more informative way rather than directly study their
8 cognitive ability. Second, categorization of problems and student performance in terms of
9 familiar course themes can more directly inform improvements in instruction. Third, most of the
10 questions have overlap among the standard cognitive categories (see further below).
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18 The definitions of most of the problem types are straightforward. An exception is the
19 broad Bonding/Concepts (2) problem type, which includes atomic and molecular wavefunctions,
20 hybridization, Lewis structures, isomers, resonance, and polar bonds as topics for the first
21 semester course, and conjugated π -molecular wavefunctions, resonance, aromaticity, and
22 retrosynthetic analysis in terms of the synthon concept in the second semester course. The
23 Nomenclature (1) problem type involves mainly IUPAC nomenclature. The Acidity/Basicity (3)
24 problem type refers to both Brønsted and Lewis acid/base concepts. The Spectroscopy (4)
25 problem type includes problems that ask about fundamental spectroscopic principles (e.g. factors
26 that determine NMR chemical shifts and IR absorption frequencies), but most of these problems
27 involve determination of an unknown structure from provided spectra. The Chirality (5) problem
28 type refers to problems that require identification and characterization of enantiomers and their
29 properties and reactions. The Mechanism (6) problem type includes simple multi-step curved
30 arrow pushing mechanism problems for both reactions the students have seen previously and
31 reactions they have never seen before. The Reagents/Products (7) problem type refers to
32 problems in which students are asked to supply missing reagents/conditions or major organic
33 product, and the Multi-Step Synthesis (8) problem type refers to problems in which students are
34 asked to provide a synthesis a target structure from a provided starting structure. The Pericyclic
35 Reactions (9) problems include both F.M.O. and aromatic transition state theory, and the
36 Conformations (10) problem type refers to conformational analysis of both cyclic and acyclic
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4 alkanes. Example questions are provided in the Appendix.
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6 To be included in the analysis, each question had to pass a standard item discrimination
7 test (Nunnally and Ator, 1964). Questions with a discrimination index of 0.2 or greater were
8 included in the analysis. Upon completion of the discrimination item analysis, the Chirality (5)
9 problem type, which included identification of isomers and assignment of absolute
10 configurations, was found to have so few problems that it could not be considered further in the
11 analysis, Table 2.
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18 Individual student scores for each discriminated question in a problem type were summed,
19 averaged by the available points for that particular problem type, and converted into a percentage.
20 Each student's overall score for all of the discriminated questions in each semester was
21 converted into a percentage of the total available points. Several scatter plots showing the
22 correlations between the students' average score for several problem types versus overall course
23 score are shown in Figure 1, for the fall 2013 semester, as an illustrative example. Qualitatively,
24 it is evident that the scatter is not the same for each problem type. For this particular semester,
25 the Mechanism (6) problem type had a lower scatter, and the Nomenclature (1) problem type, a
26 significantly higher scatter.
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39 **Student Performance by Problem Type**

40 Linear correlation analysis of performance per problem type versus overall performance was
41 performed for each semester; the relevant correlation coefficients (r) are summarized in Table 3.
42 All problem types were positively correlated to the overall performance, and the correlation
43 coefficients (r) varied over a very wide range, from 0.44 to 0.93. The Mechanism (6) problem
44 type consistently exhibited the highest correlations for both semesters, whereas the
45 Nomenclature (1) problem type was always among the least correlating problem types.
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53 Stepwise multiple linear regression was also performed as a way of simultaneously
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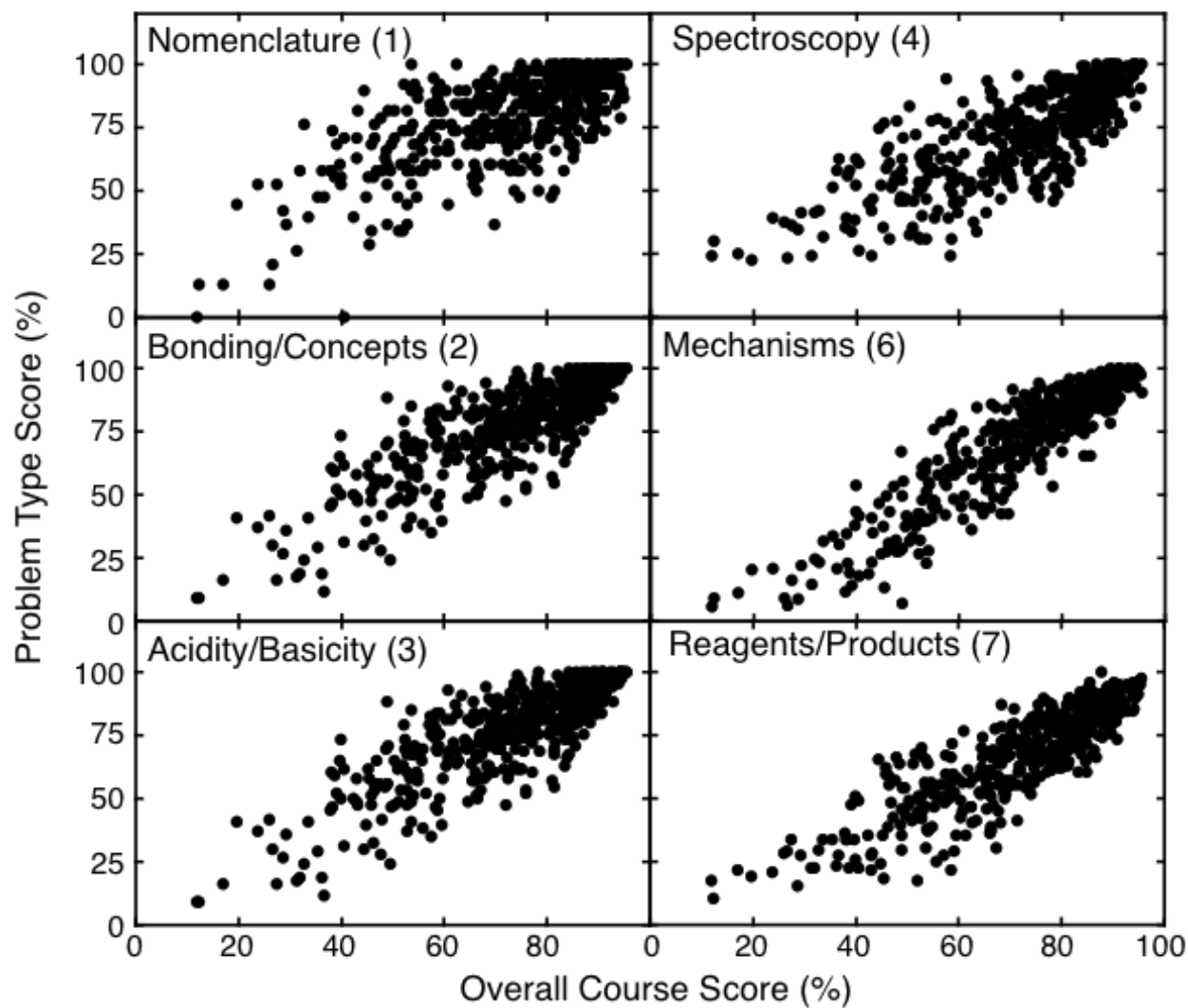


Figure 1. Scatter plots of percentage scores for various types of organic chemistry problem versus overall course percentage score, for the fall 2013 first semester organic chemistry class as an example, showing different correlations for different problem types.

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4 analyzing all of the data. The different problem types were treated as the predictor variables to
5 account for the variance in the overall class performance. As an example, the results of the
6 stepwise multiple linear regression analysis for the fall 2013 semester of Figure 1, are
7 summarized in Table 4. For this particular semester, data was available for seven problem types,
8 Table 2, which were used as the predictor variables in the analysis. The final model, $F(5, 453)=$
9 $20306.1, p=.000, R^2=.996$, did not include two of the problem type predictor variables,
10 Nomenclature (1) and Acidity/Basicity (3), since these did not increase the predictive value of
11 the final scores. As expected from Figure 1 and Table 3, the Mechanism (6) problem type was
12 the most predictive of overall class performance, $\beta=.915, F(1, 453)=2343.2, p=.000, \text{adj.}$
13 $R^2=.836$, followed by the Bonding/Concepts (2) problem type, which accounted for an additional
14 12% of the variance of the overall class performance. The other problem types, Conformations
15 (10), Spectroscopy (4), and Reagents/Products (7), accounted for only an additional 2.8%, 1.1%,
16 and 0.9% of the variance respectively
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31 The problem types that were the highest predictors of variance in the overall class
32 performance for each semester are summarized in Tables 5 and 6. As mentioned above, the class
33 performances were not identical in terms of mean students scores from semester to semester,
34 nevertheless, the same problem types were found to be the highest predictor variables each
35 semester. For the first semester course, the Mechanism (6) problem type was always the highest
36 predictor variable; the second highest predictor was always the Bonding/Concepts (2) problem
37 type, Table 5. The third highest predictor variables varied among Reagents/Products (7),
38 Conformations (10), and Acidity/Basicity (3) problem types. For the second semester course, the
39 highest predictors were always Mechanism (6), Multi-Step Synthesis (8), and Reagents/Products
40 (7) problem types. The problem type Nomenclature (1) was almost always the least predictive
41 problem type for both semesters.
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53 The most predictive problem types were those that were more likely to be characterized
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Table 3 Correlation Coefficients for Linear Regression Analysis of Student Performance by Problem Type for All Semesters

Problem Type	First Semester (Fall)					Second Semester (Spring)				
	2009	2010	2011	2012	2013	2010	2011	2012	2013	2014
Nomenclature (1)	.75	.59	.65	.76	.70	.68	.44	.74	.72	.74
Bonding/Concepts (2)	.86	.83	.88	.88	.88	.39	.47	--	.54	.54
Acidity/Basicity (3)	.70	.74	.61	.85	.83	.69	.71	.55	.71	.73
Spectroscopy (4)	.75	.71	.83	.84	.79	.68	.62	.58	--	--
Mechanism (6)	.94	.94	.92	.92	.92	.89	.88	.95	.89	.91
Reagents/Products (7)	.90	.90	.91	.91	.87	.94	.94	.96	.96	.95
Synthesis (8)	--	--	--	--	--	.96	.95	.95	.95	.93
Pericyclic Reactions (9)	--	--	--	--	--	.70	.68	.76	.76	.78
Conformations (10)	.75	.79	.88	.89	.87	--	--	--	--	--

Table 4 Stepwise Multiple Linear Regression Analysis of Student Performance by Problem

Type for the Fall 2013 First Semester Organic Chemistry Class

Variable	Model 1			Model 2			Model 3			Model 4			Model 5		
	B1	SE _B	β	B2	SE _B	β	B3	SE _B	β	B4	SE _B	β	B5	SE _B	β
Constant	24.0	1.05		8.23	.775		4.91	.551		2.14	.442		1.51	.251	
Mechanism (6)	.670	.014	.915	.424	.011	.579	.328	.009	.447	.282	.007	.385	.226	.004	.309
Bonding/Concepts (2)				.445	.014	.474	.350	.011	.373	.331	.008	.352	.319	.005	.340
Conformations (10)							.223	.010	.271	.189	.007	.230	.145	.005	.177
Spectroscopy (4)										.140	.007	.156	.127	.004	.141
Reagents/Products (7)													.146	.005	.169
R	.915			.974			.988			.994			.998		
R ²	.837			.948			.976			.987			.996		
Adj. R ²	.836			.948			.976			.987			.996		

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4 by higher categories of cognitive domain. In the first semester course, the Bonding/Concepts (2)
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6 problem type includes the majority of the new concepts that students are exposed to in first
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8 semester organic chemistry. Only a limited number of chemical reactions are covered in the first
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10 semester course, and the conceptual basis for these reactions are mostly covered by
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12 Bonding/Concepts (2) problems, which means that Bonding/Concepts (2) carries a much higher
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14 cognitive load than Reagents/Products (7) in the first semester course. The second semester
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16 course focuses much more on chemical reactions, and new concepts are introduced more within
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18 the context of new reactions, which places a much higher cognitive load on Reagents/Products (7)
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20 in the second semester course. Multi-step synthesis (Synthesis (8)) is taught in the second
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22 semester course and requires a deep understanding of concepts and reactions by the students,
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24 which is highly cognitively demanding. Multi-step synthesis is also challenging for students
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26 because they are required to solve problems they have never seen before and that by definition
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28 are impossible to memorize. Mechanism problems (6) are also cognitively demanding for
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30 students in both the first and second semester classes since they are again required to solve
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32 problem they have never seen before and obviously cannot memorize.
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35 One potential problem with the simple linear regression analyses is that the scores for
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37 each student were averaged over different numbers of problems for each type. Types for which
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39 there were a larger number of problems might be expected to correlate better with overall
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41 performance on that basis alone. However, the types with the larger numbers of problems did not
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43 always exhibit the best correlations and/or were the best predictors. For the fall 2013 semester,
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45 for example (Figure 1 and Table 3), the Mechanism (6) problem type, which had 6 problems,
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47 was a better predictor of the overall performance than the Bonding/Concepts (2) problem type,
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49 which had 10 problems. The Reagents/Products (7) problem type, which had 3 problems, was a
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51 better predictor variable than the Conformations (10) problem type for which there were 5
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53 problems. In addition, the standardized coefficients from the stepwise linear regression (Tables
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Table 5 The Most Predictive Problem Types from Stepwise Multiple Linear Regression for the First Semester Organic Chemistry Course.^a

	Fall 2009		Fall 2010		Fall 2011		Fall 2012		Fall 2013	
	Model 1	Model 3	Model 1	Model 3	Model 1	Model 3	Model 1	Model 3	Model 1	Model 3
Prob. Types	(6)	(6),(2),(7)	(6)	(6),(2),(10)	(6)	(6),(2),(7)	(6)	(6),(2),(3)	(6)	(6),(2),(10)
R	.937	.987	.935	.985	.924	.986	.920	.984	.915	.988
R ²	.879	.974	.875	.969	.854	.971	.847	.967	.837	.976
Adj. R ²	.878	.974	.875	.969	.854	.971	.847	.967	.836	.976

^a Model 1 describes the single most predictive problem type, Model 3 describes the three most predictive problem types in decreasing order of predictive value. The problem types are summarized in Table 2.

Table 6 The Most Predictive Problem Types from Stepwise Multiple Linear Regression for the Second Semester Organic Chemistry Course.^a

	Spring 2010		Spring 2011		Spring 2012		Spring 2013		Spring 2014	
	Model 1	Model 3	Model 1	Model 3	Model 1	Model 3	Model 1	Model 3	Model 1	Model 3
Prob. Types	(8)	(8),(6),(7)	(8)	(8),(6),(7)	(7)	(7),(6),(8)	(7)	(7),(6),(8)	(7)	(7),(8),(6)
R	.955	.991	.954	.992	.956	.998	.957	.993	.946	.992
R ²	.912	.983	.910	.984	.913	.995	.916	.985	.895	.984
Adj. R ²	.912	.983	.910	.984	.913	.995	.916	.985	.894	.984

^a Model 1 describes the single most predictive problem type, Model 3 describes the three most predictive problem types in decreasing order of predictive value. The problem types are summarized in Table 2.

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4 - 6) are intrinsically corrected for different numbers of problem types, and the observed trends
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4 - 6) are intrinsically corrected for different numbers of problem types, and the observed trends in terms of which problem types are most predictive of performance are the same for both analyses. Thus, the observed behavior are not determined by the number of discriminated problems.

Two other statistical problems potentially influence the results of both the linear and the stepwise regressions, however. The scatter plots of Figure 1 show clear ceiling effects, particularly for Nomenclature (1), Bonding/Concepts (2), and Acidity/Basicity (3) problem types. The scatter plots also show somewhat different extents of deviation from normal distribution for the different problem types. To ameliorate these effects, a simple non-parametric data analysis method was also used. Students were ranked in terms of percentage scores from lowest to highest both in terms of the overall class performance and for each problem type. For each problem type, the percentage of students who were in both the lower half in that problem type and in also in overall class performance was then obtained. The larger this percentage, the more that particular problem type was representative of overall performance. The percentages ranged from a low of 67% to a high of 93%, depending upon the problem type and the semester, Table 7. The averages of these percentages over the five semesters for each course, Table 6, showed that the Mechanism (6), Bonding/Concepts (2), and Reagents/Products (7) problem types were those that best correlated with the overall performance in the first semester course, and that the Mechanisms (6), Reagents/Products (7), and Synthesis (8) problem types were the most correlating in the second semester class. The problem types that were best correlated with overall performance were thus found to be essentially the same from all of the different methods of analysis.

Another possible issue is that the instructor was the same for all classes, and the observations may be a consequence of instructor bias. Specifically, certain problem types may be more predictive of overall performance simply because they were emphasized to a greater or

Table 7 Percentage of Students by Problem Type Who Were in Both the Lower Half of the Class Overall and the Lower Half in That Problem Type

Problem Type	First Semester (Fall)						Second Semester (Spring)					
	2009	2010	2011	2012	2013	Avg. ^a	2010	2011	2012	2013	2014	Avg. ^a
Nomenclature (1)	77	69	74	79	72	74(4.0)	74	76	75	79	77	76(1.9)
Bonding/Concepts (2)	85	84	84	84	87	85(1.3)	68	67	--	76	79	73(5.9)
Acidity/Basicity (3)	76	73	68	83	81	76(6.1)	76	76	69	80	76	75(4.0)
Spectroscopy (4)	73	77	85	81	80	79(4.5)	74	67	73	--	--	71(3.8)
Mechanism (6)	89	87	85	86	87	87(1.5)	84	87	91	91	90	89(3.0)
Reagents/Products (7)	85	86	86	86	84	85(0.9)	88	87	91	91	90	89(1.8)
Synthesis (8)	--	--	--	--	--	--	90	89	93	90	91	91(1.5)
Pericyclic Reactions (9)	--	--	--	--	--	--	73	70	83	76	78	76(5.0)
Conformations (10)	77	82	84	87	82	82(3.6)	--	--	--	--	--	--

^a The numbers in parentheses are the standard deviations

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4 lesser extent by the instructor. However, emphasis or de-emphasis of a specific topic might be
5 expected to lead to universally high (emphasis) or low (de-emphasis) performance for all
6 students in that topic, and this is clearly not the case for the problem types are are highly
7 predicting. For a problem type to be highly predicting the students scores need to span the entire
8 range of the overall scores. Thus, although we recognize the limitations of only using data from
9 a single instructor, we believe that instructor bias is unlikely to be responsible for the trends
10 across problem type observed here. It is possible that different instructors could write problems
11 that distribute the cognitive load differently, but the conclusion that students are more
12 differentiated by problems with a higher cognitive load seems reasonable, even if the types of
13 problems with the higher cognitive load might be different from those in this study.
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27 **Connecting Performance to Student Characteristics**

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29 Even though the overall class performance was not identical for the classes included in this study,
30 the data show quite reproducibly that student performance is not the same across all problem
31 types. The problem types that are more cognitively demanding tend to be better predictors of
32 overall performance, sometimes with remarkably high predictive value. The differences in
33 performance between problem types were still fairly small, however, which may be due to the
34 inherent difficulty of cleanly categorizing some of the questions into a single problem type, and
35 also because many questions draw from different cognitive categories. For example, in addition
36 to applying memorized rules, the nomenclature questions in these courses also require students to
37 be able to recognize and assign the stereochemistry of geometrical isomers and also at
38 asymmetric centers. Inevitable mixing of concepts within questions will tend to reduce the
39 differences between the problem types.
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52 Nevertheless, it was of interest to try to relate performance by problem type to influences
53 on student performance discussed in the literature. We have analyzed three of these: 1) first
54 semester general chemistry grade, 2) whether the student is a first generation college goer, 3)
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4 whether the student self-reports as a pre-health student. Data for this part of the study was
5 collected by survey of first semester fall 2013 class. Survey participation was voluntary, but 81%
6 of the class participated and so the results should be quite representative. The relevant data are
7 summarized in Table 8.
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12 Prior achievement in science courses has previously been found to be a good predictor of
13 organic chemistry performance (see, for example, Turner and Lindsay, 2003; Lopez *et al.*, 2014).
14 Table 8 shows a clear trend between general chemistry grade and overall class performance. The
15 results from the analysis of variance for overall class performance shows a statistically
16 significant difference in overall scores by general chemistry grade, $F(2,353)=39.6, p=.000$. The
17 Tukey-Kramer post-hoc test shows that both the 'A' and 'B' students ($p=.000$) and the 'A' and 'C'
18 students ($p=.000$) are statistically different, but the 'B' and 'C' students are not ($p=.097$),
19 presumably because the population of 'C' students is so small, Table 8. Therefore, to determine
20 whether performance difference varied with problem type, the 'B' and 'C' student mean scores
21 were combined and compared to those of the 'A' students. The largest difference between these
22 scores was found for the Bonding/Concepts (2) and Mechanisms (6) problem types, and the
23 smallest difference was found for the Nomenclature (1) problem type. These results exactly
24 match the overall trends discussed above, i.e., that lower performing general chemistry students
25 are differentiated from higher performing general chemistry students to a greater extent by
26 problem types that have higher cognitive demand. General chemistry grade is, however, a
27 predictor of organic chemistry performance, and does not describe a fundamental student
28 characteristic.
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48 A more fundamental characteristic that may contribute to success is whether students are
49 first-generation college goers (Richardson and Skinner, 1992; Horn and Nunez, 2000; Pascarella
50 *et al.*, 2004). The overall mean scores and the mean scores across problem type were found to be
51 numerically lower for first-generation college goers in the fall 2013 class, Table 8. The
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Table 8 Comparison of Student Mean Percent Scores by Pre-Health, First Generation College Goers and General Chemistry Grade for the First Semester Fall 2013 Class

Student ^a	Overall	Category							
		(1)	(2)	(3)	(4)	(6)	(7)	(10)	
Not Pre-Health (116)	73.0	78.6	76.5	76.9	73.9	73.3	67.0	78.3	
Pre-Health (254)	72.2	78.9	74.8	76.4	73.0	72.3	68.2	77.4	
Not First-Generation (99)	73.7	79.4	76.9	77.3	75.0	73.9	68.8	78.8	
First-Generation (271)	68.9	77.2	71.1	74.4	68.7	68.9	65.1	74.6	
Gen. Chem Grade A (216)	78.0	83.5	81.7	81.0	77.7	79.3	72.9	83.1	
Gen. Chem Grade B (108)	65.0	72.5	67.3	70.4	67.1	63.6	61.1	69.4	
Gen. Chem Grade C (32)	58.5	67.1	59.1	64.7	61.3	56.7	54.9	65.1	
B + C Grades (140) ^b	63.5	71.2	65.4	69.1	65.8	62.0	59.7	68.4	

^a The number of students in each category is given in parenthesis

^b Combined mean scores for 'B' and 'C' general chemistry students. Student who earned a lower grade than C are not allowed to register for the organic chemistry course at the subject institution.

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4 differences in this case, however, were considerably smaller than observed with general
5 chemistry grade. The overall mean scores were found to be statistically different, $t(368)=2.42$,
6 $p=.016$, but only the Bonding/Concepts (2) and Spectroscopy (4) problem types' mean scores
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8 were also found to be statistically different. We conclude that although this characteristic does
9
10 influence student performance, the effect is too small to be analyzed by problem type.
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14 As mentioned above, organic chemistry is often seen as a roadblock for the students on
15 pre-health tracks in the United States (Lovecchio and Dundes, 2002; Barr *et al.*, 2000). The
16 performances of pre-health and non-pre-health students in terms of both overall score and across
17 the problem types were compared, Table 8. For the fall 2013 class, there was no significant
18 difference in overall mean scores, $t(368)=.406$, $p=.685$. There was also no statistical difference
19 in the mean scores between these two groups for any of the problem types.
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23 The characteristic that differentiates strongly between students in terms of overall
24 performance (general chemistry grade) also differentiates by the cognitive demand of the
25 problem type. The characteristic that barely differentiates students by overall performance (first
26 generation college goer) also barely differentiates by problem type. The characteristic that does
27 not differentiate students (pre-health versus not pre-health) also does not differentiate by problem
28 type. If this connection between student characteristic and performance is general, then it is
29 quite revealing. It implies that characteristics that contribute to higher overall performance, also
30 contribute to higher performance on problems with higher cognitive load, even if they have no
31 direct connection to cognitive ability. It also implies that characteristics that do not substantially
32 contribute overall performance do not influence performance on problems with differing
33 cognitive loads, even if a connection to cognitive ability might be expected. We cannot be sure
34 of this since we have not yet studied enough different kinds of student characteristics, but it is
35 important enough to explore further implications anyway.
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39 If general chemistry grade is predictive of overall performance in organic chemistry, and
40 higher performing general chemistry students perform better on the more cognitively demanding
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4 problems in organic chemistry, then this would suggest that the cognitive skills required to
5 perform well in organic chemistry are similar to those required to do well in general chemistry.
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7 However, it is often discussed in the literature that the quantitative emphasis in general chemistry
8 is quite different from the qualitative emphasis of organic chemistry (Ferguson and Bodner, 2008;
9 Lopez *et al.*, 2014). Thus, it is unlikely that the relationship between general chemistry and
10 organic chemistry performance is purely a consequence of similar student cognitive abilities. Of
11 course, student performance is also strongly influenced by other fundamental factors, specifically
12 motivation (Black and Deci, 2000; Turner and Lindsay, 2003; Zusho *et al.*, 2003; Koballa and
13 Glynn, 2007; Jurisevic *et al.*, 2012; Richardson *et al.*, 2012) and cultural capital (Tai *et al.*, 2005;
14 Hailikari and Nevgi, 2010; Szu *et al.*, 2012). The larger the influence of, for example,
15 motivation on student performance, the more likely it will be that students who are high
16 performing in general chemistry will also be high performing in organic chemistry, since the
17 cognitive influence is diminished. We suggest that the results described here point to the
18 important contribution of factors in addition to cognitive skills to student success in organic
19 chemistry (Black and Deci, 2000; Lynch and Trujillo, 2011).
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37 **Conclusions**

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39 Quantitative analysis of performance across problem types is a readily accessible tool that
40 provides insight into influences on student performance for factors that have a substantial
41 influence on performance. Whether students are first generation college goers only weakly
42 influences performance and analysis by problem type is not possible. General chemistry grade,
43 however, is a strong predictor of organic chemistry performance and problem-type analysis
44 clearly points to the important role of non-cognitive factors such as student motivation. This
45 work clearly needs to be expanded to include quantitative studies of other kinds of student
46 characteristics and also qualitative analysis of student approaches to the general organic
47 chemistry course, and both of these are currently underway in our research groups.
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6 **Acknowledgement**
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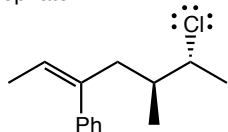
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Appendix

Example Questions from Fall 2009 First semester Course

Nomenclature (1) type question

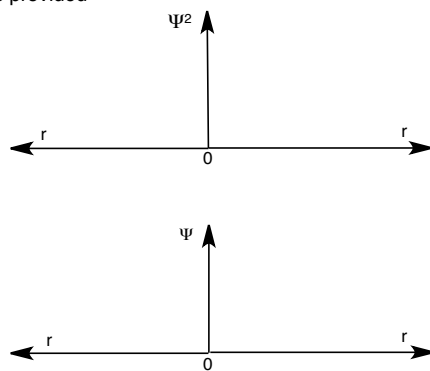
Question 1 (14 pts.) Give the IUPAC name for the following. Specify stereochemistry as appropriate.

*Bonding/Concepts (2) type question*

Question 2 (18 pts.) Given the pictorial representation of the 3p atomic orbital shown below:

a) Give a plot of the magnitude of the wavefunction (Ψ) versus distance from the nucleus on the axes provided, **AND IDENTIFY ANY NODES ON THIS PLOT**

b) Give a plot of the magnitude of the wavefunction squared (Ψ^2) versus distance from the nucleus on the axes provided



3p A.O.
wavefunction
picture

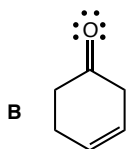
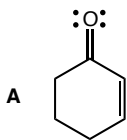
*Acidity/Basicity (3) Question type*

Question 1 (22 pts.) Which of the following two structures would you expect to be the strongest Bronsted acid? Give an explanation for your choice. Your explanation should include drawings of the structures of the corresponding conjugate bases, as appropriate (ignore other possible structure isomers).



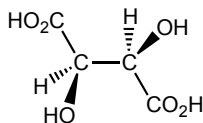
Spectroscopy (4) Question Type

Question 7 (22 pts.) Between structure **A** and **B**, which should have a **LOWER** frequency IR absorption for the C=O bond? Give an explanation that includes drawings of relevant minor resonance contributors.

**Chirality (5) Question Type**

Question 2 (12 pts.)

- a) Assign the configuration, R or S, for each asymmetric (chiral) center for (-) tartaric acid
 b) Draw a structure of (+) tartaric acid

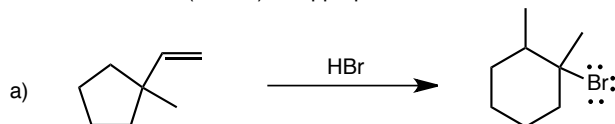


(-) tartaric acid

(+) tartaric acid

Mechanism (6) Question Type

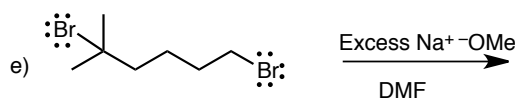
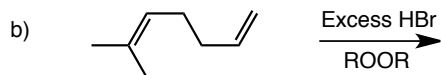
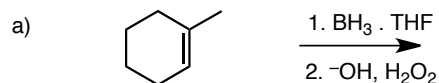
Question 11 (60 pts.) For the each of the following reactions, give a full curved-arrow pushing mechanism. At each step indicate the Lewis acid and base (LA/LB) and also Bronsted acid and base (BA/BB) as appropriate.



Reagents/Products (7) Question Type

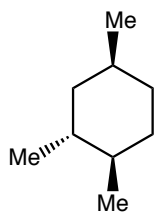
Question 7 (77 pts.) For the following reactions:

- a) Give the missing major **ORGANIC PRODUCT** or **REAGENTS/CONDITIONS** as appropriate
 b) **Show stereochemistry** where appropriate
 c) **Briefly explain whether a solution of the product would be optically active**

**Conformations (10) Question Type**

Question 4 (22 pts) For the following structure

- a) draw **both chair conformations**
 b) determine the **energy difference** between the two chair conformations
 c) indicate the **lower energy chair**

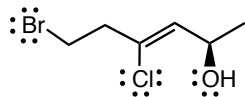


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Example Questions from Spring 2010 Second Semester Course

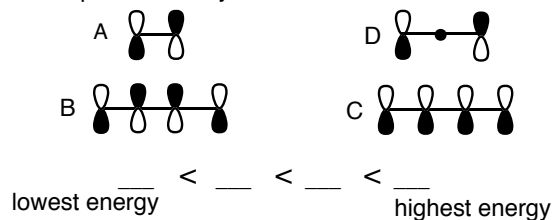
Nomenclature (1) type question

Question 3 (12 pts.) Give the IUPAC name for the following compound. Be sure to use cis/trans, E/Z or R/S where appropriate.



Bonding/Concepts (2) type question

Question 2 (10 pts.) Rank the energies of an electron in each of the following π -molecular orbitals. Give a BRIEF explanation for your choice.



Acidity/Basicity (3) type question

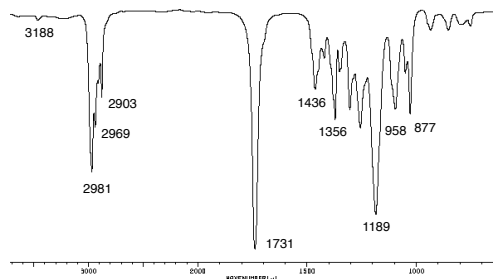
Question 4 (14 pts.) Which is the stronger Bronsted acid, A or B? Give a BRIEF explanation, including the drawings of all relevant structures and ALL resonance contributors as appropriate.



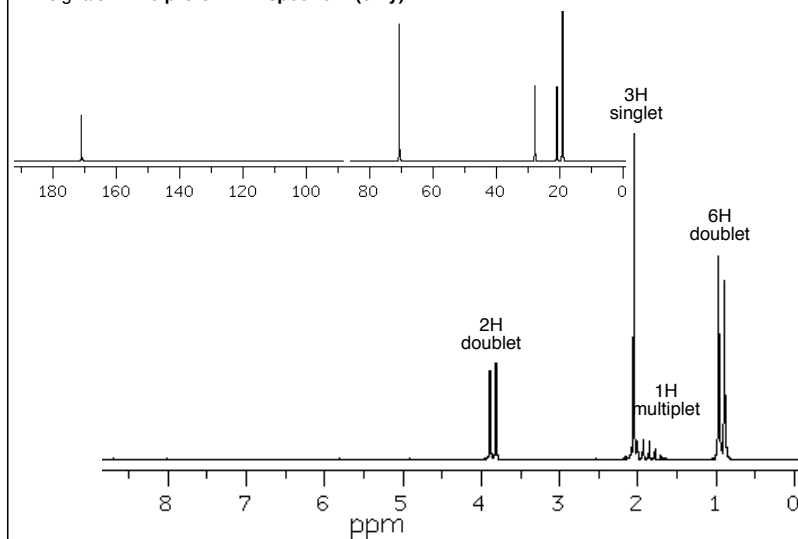
Spectroscopy (4) type question

Question 13 (25pts) Provided are spectra for a compound with molecular formula $C_6H_{12}O_2$

a) Give the degrees of unsaturation _____

b) On the infrared spectrum, indicate the peaks that identify the functional groups in the molecule (including $C(sp^3)-H$). Indicate **BOTH the functional group**, and where appropriate, **the specific BOND** in the functional group that corresponds to the peak.

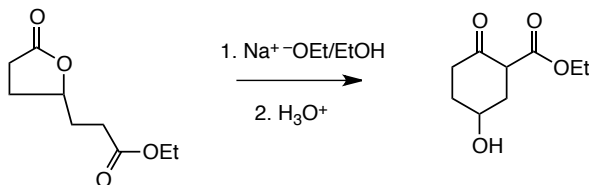
c) draw the structure and clearly indicate which hydrogens correspond to which signals in the proton nmr spectrum (only)



Mechanism (6) problem type

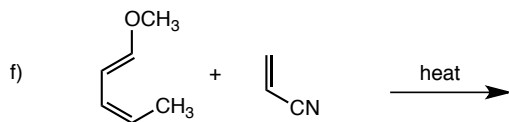
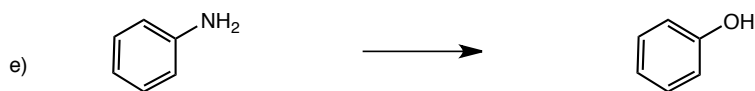
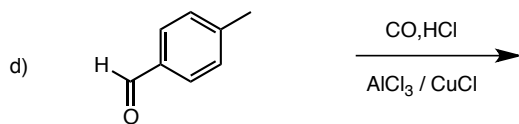
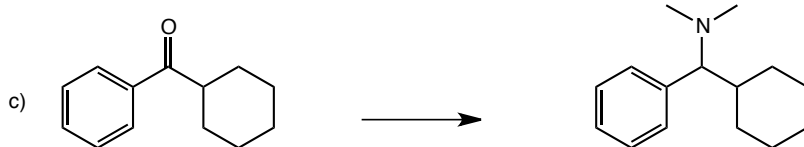
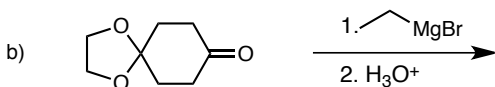
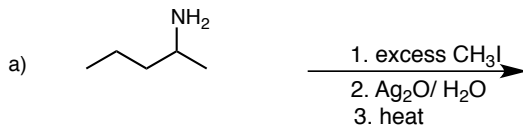
Question 12 (20 pts.) Give a curved arrow-pushing mechanism for the following reaction

- You can give an "abbreviated mechanism, i.e. you may use $+H^+$ and $-H^+$
- IT IS NOT NECESSARY TO INDICATE THE LEWIS/BRONSTED ACID/BASE AT EACH STEP
- **BUT, draw all resonance structures for the intermediates**
- Add non-bonding electrons and C–H bonds as necessary

**Reagent/Products (7) question type**

Question 8 (72 pts)

Provide the missing products, reagents/conditions or reactants, as required. **Do not forget to include absolute and relative stereochemistry as appropriate.**



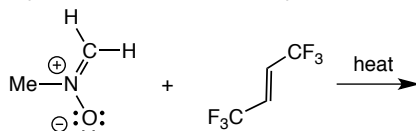
Synthesis (8) question type

Question 16 (40 pts.) In each case, synthesize the (target) molecules on the right from the starting molecules the left. this can not be done in one reaction. Give reagents and conditions and the intermediate molecules at each step. Do not show any mechanisms or transient intermediates.

**Pericyclic Reactions (9) question type**

Question 9 (18 pts)

a) Give the curved arrow-pushing and the allowed product for the following cycloaddition reaction. Pay attention to stereochemistry



b) ON TOP of the structures as indicated, draw the requested F.M.O.s and give the total number of π -molecular orbitals and electrons associated with the π -system for each structure.

