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Acid–Base Learning Outcomes for Students in an Introductory Organic Chemistry Course

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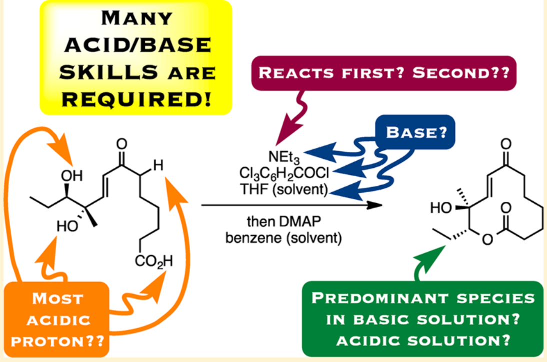
S Supporting Information



ABSTRACT: An outcome-based approach to teaching and learning focuses on what the student demonstrably knows and can do after instruction, rather than on what the instructor teaches. This outcome-focused approach can then guide the alignment of teaching strategies, learning activities, and assessment. In organic chemistry, mastery of organic acid–base knowledge and skills are particularly essential for success. For example, Brønsted acid–base knowledge and skills are required in greater than 85% of the more complex organic and biochemical reactions we analyzed in this study. Despite the importance of mastering acid–base concepts and skills, the literature describes many related student difficulties. We identified essential learning outcomes (LOs) in organic acid–base chemistry by (1) analyzing more complex organic reactions to identify the acid–base-related skills and knowledge that students would need to successfully analyze those reactions and (2) analyzing textbooks' explanations and coverage of acid–base chemistry. We constructed the learning outcomes using the Structure of Observed Learning Outcomes (SOLO) and modified Bloom taxonomies, as well as SMART (specific, measurable, achievable, relevant, and time-bounded) goal-setting principles. We explicitly aligned our courses' learning activities and assessments with those intended learning outcomes, both in the initial introduction of acid–base chemistry and as we analyze more complex reactions. To clearly communicate these LOs to students and other educators, we described them in an educational graphic.

KEYWORDS: *First-Year Undergraduate/General, Second-Year Undergraduate, Organic Chemistry, Brønsted-Lowry Acids/Bases, Constructivism, Acids/Bases*

INTRODUCTION

The Brønsted acid–base reaction is the first chemical reaction most organic chemistry students learn, and almost every subsequent reaction learned necessitates an acid–base (the Brønsted definition is used throughout, unless explicitly stated otherwise) step at some point in the reaction or purification (described in detail herein). Although functionally simple—an acid–base reaction involves the transfer of a single proton—many chemical concepts are involved in acid–base chemistry, such as energetics, concentrations, electronegativity, resonance, and mechanisms.

Despite the centrality of acid–base reactions in organic chemistry curricula and the prevalence of acid–base reactions in our world, the hundreds of thousands of students who study acid–base chemistry struggle in many ways, including making many errors and holding misconceptions.[1−5] High school students develop misconceptions[4−12] and many high school teachers have misconceptions regarding acid–base concepts that would be passed on to students.[13]

Many misconceptions continue into university. In particular, students in one study were confused by acid–bases definitions (e.g., mixing Arrhenius and Brønsted models or equating pH with acid–base strength) and had difficulty providing examples of bases.[14] Student difficulties applying simple acid–base concepts to biochemistry problems have been reported.[15,16]

Acid/base chemistry continues to present difficulties to students in university-level organic chemistry courses.[16−18] Cartrette and Mayo[19] reported that (1) every participant in their study defined acids using the Brønsted definition and few correctly used the Lewis definition; (2) pH was equated with acid–base strength; (3) students had difficulty correlating the terms acid–base with electrophile/nucleophile; and (4) most students had difficulty explaining relative acid strengths, although they generally knew that structural motifs could explain physical behavior. Undergraduate students have used mental models of organic acid–base chemistry created more from their (often incorrect) intuition or incorrectly applied heuristic reasoning to solve acid–base problems rather than using scientific reasoning.[20,21] Even at the graduate level, organic chemistry students had poorly developed conceptions of acids and they analyzed acid–base chemistry from a single physical construct (i.e., bond polarization) rather than taking a multivariate approach.[22]

We developed a set of learning outcomes (LOs) for organic acid–base chemistry, described herein, to help improve student learning and encourage student **mastery** of acid–base concepts. Learning outcomes refer to the knowledge and skills that the students **demonstrate** at the end of the course.[23] Here, we use the expression "intended learning outcomes" (ILOs) to mean what the instructor wants students to be able to know and do by the end of the course. A focus on LOs helps bring teaching strategies, learning activities, and assessments into alignment (Figure 1). Clearly communicated learning outcomes also allow students to track their own learning progress.

Figure 1. Intended learning outcomes can inform teaching strategies, learning activities, and assessment to achieve desired learning outcomes.

We initially constructed a set of ILOs based on our teaching and learning experiences. We improved these ILOs by determining the organic acid–base knowledge and skills required to analyze more complex organic reactions and identifying the topics covered in organic textbooks. We created learning activities that targeted the most important ILOs and known student difficulties (e.g., common errors and misconceptions). In this work, we did not explicitly address other aspects that are essential to deep learning and conceptual change, such as motivation[2] and metacognition.[24] Our process is described in detail below.

KNOWLEDGE AND SKILLS REQUIRED TO ANALYZE MORE COMPLEX ORGANIC REACTIONS

To identify essential LOs for acid–base chemistry, we analyzed many more complex organic and a few biochemical reactions. First, we determined the frequency of occurrence of acid–base reactions in other organic and biochemical reactions that are commonly taught in organic chemistry and biochemistry courses. We analyzed twenty-five organic (e.g., S_N1, S_N2, aldol condensation)[25,26] and three biochemical reactions (e.g., Krebs cycle)[27] to determine if there was a Brønsted acid–base step present in the mechanism, required to generate the nucleophile or electrophile, or required in the workup (Figure 2). For example, the base-promoted aldol reaction requires a base to generate the enolate ("nucleophile preparation"); electrophilic aromatic substitution reactions require a deprotonation to regenerate aromaticity in the final step of the "main mechanism." Two researchers independently coded the reactions, discussed their results after coding the first few reactions to ensure consistency in the coding system, and finished with over 95% of reactions coded identically.

Of the 28 reactions analyzed, 86% required a Brønsted acid–base step in at least one phase of the reaction (e.g., to deprotonate the nucleophile). More specifically, 82% required an acid–base step as an integral part of the mechanism at least some of the time; 71% involved a Brønsted acid–base step in the mechanism every time. In every reaction variant, more than 20% of reactions required an acid–base step to prepare either the nucleophile or the electrophile, and at least two-thirds of reactions involved proton transfers to neutralize the final product (e.g., Grignard reactions). The prevalence of Brønsted acid–base steps in reactions highlights the need for student mastery of acid–base concepts. If they do not have a firm grasp on those concepts, how could they learn more complex reactions?

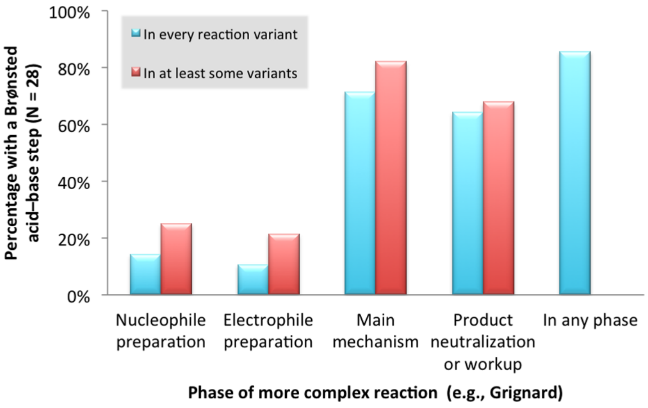
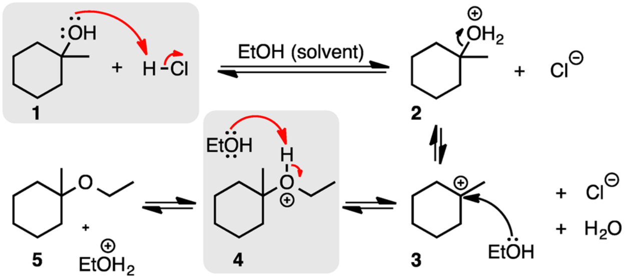


Figure 2. Prevalence of Brønsted acid–base steps in more complex organic reactions (N = 28).

We next analyzed the mechanisms of each of the reactions[25−27] to identify the acid–base-related knowledge and skills that students would need to be able to analyze and solve problems related to those reactions. For example, in the S_N1 reaction shown in Scheme 1, students must be able to identify 1-methylcyclohexanol (**1**) as a base, draw the mechanism and product (**2**)—the conjugate acid—of the acid–base reaction between the hydroxyl and the HCl, or more accurately (but increasing the complexity), they must be able to recognize that HCl and EtOH (solvent) would form $EtOH_2^+$ and Cl^-, then the 1-methylcyclohexanol (**1**) would react with the $EtOH_2^+$. To obtain the final product (**5**), they must identify its conjugate acid (**4**) as an acid, identify an appropriate base to deprotonate the oxonium, draw that mechanism, and draw the final product (the conjugate base). To understand an explanation, they must be able to interpret the terms: protonate, deprotonate, acid, base, conjugate acid, and conjugate base. Simple proton transfers are more complex than they might first appear, especially when situated in the context of another reaction.

Scheme 1. S_N1 Reaction Mechanism Features Two Acid–Base Steps



One researcher used the type of analysis described above to code the same 28 reactions (as in the previous section) according to the acid–base knowledge and skills (LOs) required for each reaction. The results are summarized in Figures 3–6. A second researcher independently followed the same procedure for five of the reactions (~20%). After

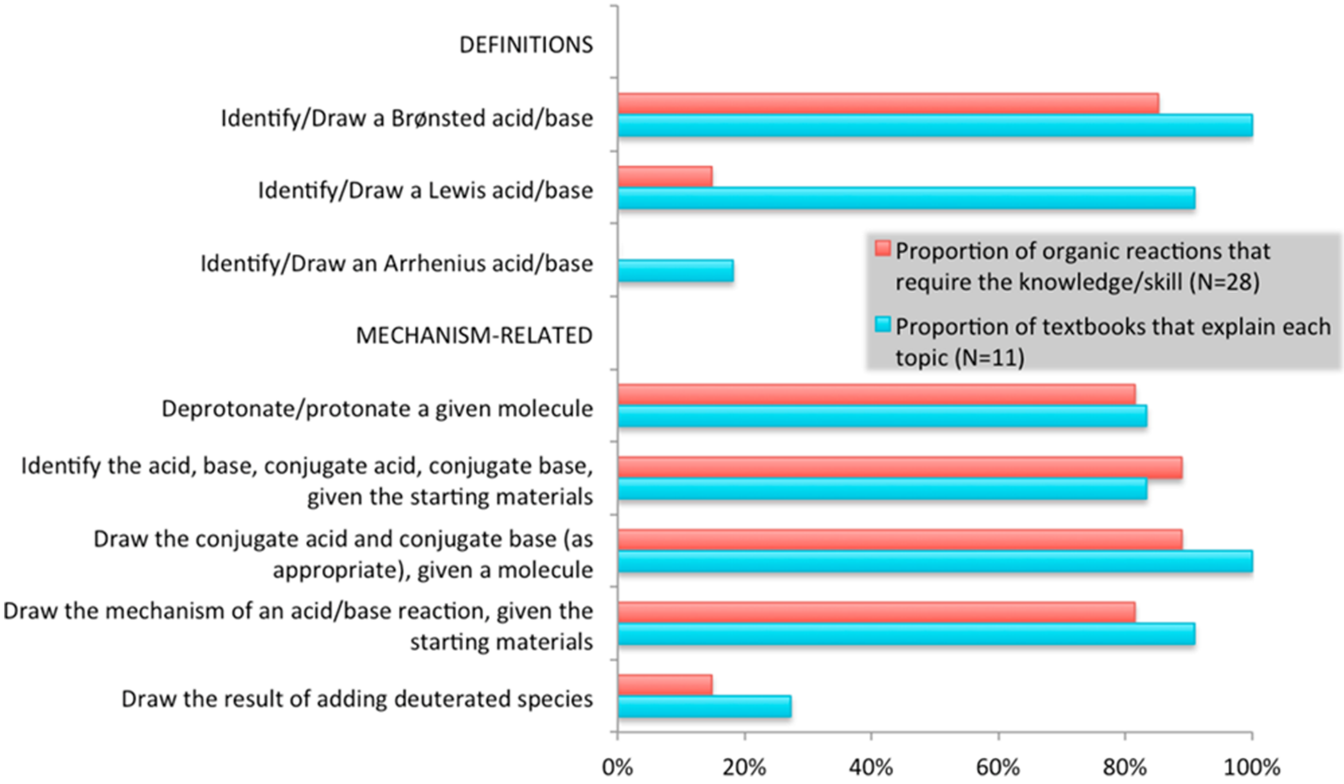


Figure 3. Proportion of organic reactions that require each LO and textbooks that explained the topic related to each LO: acid−base definitions and mechanisms.

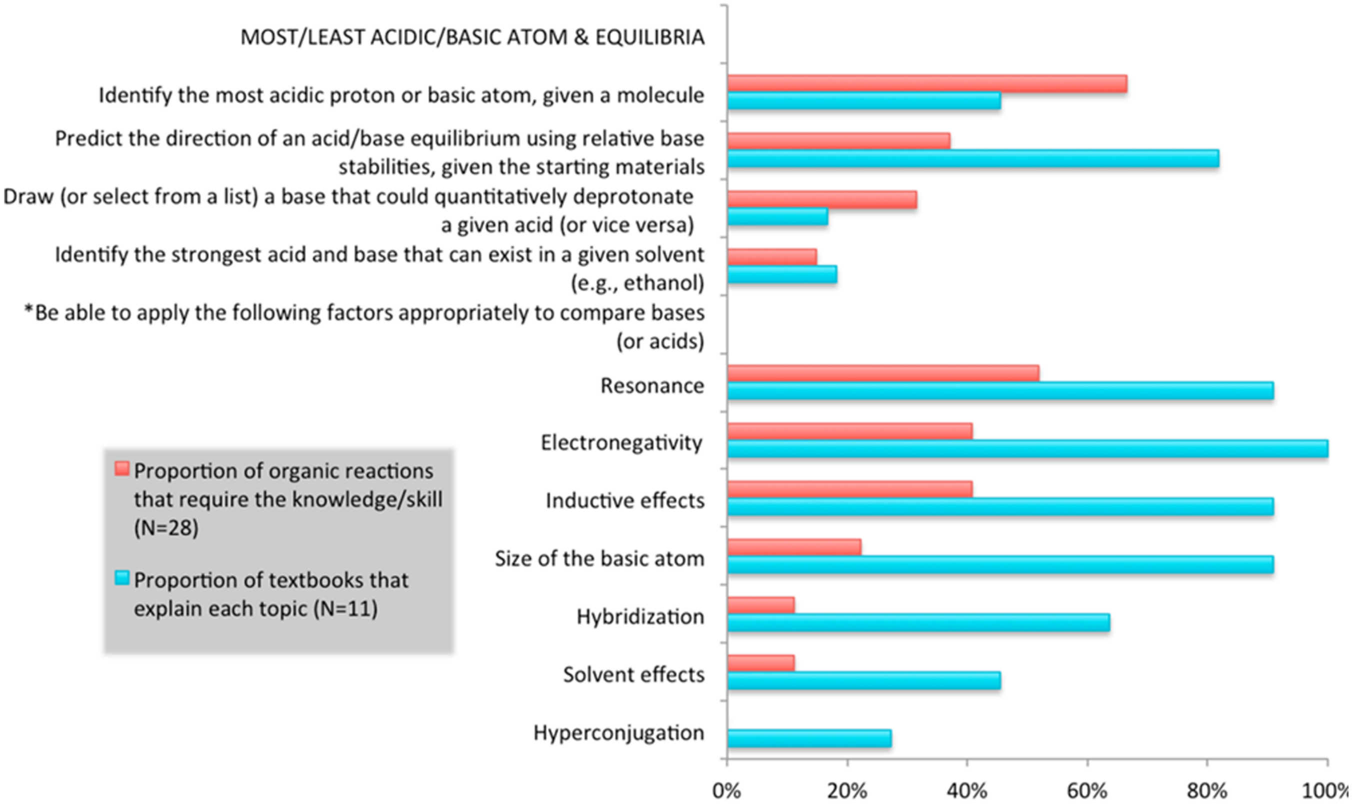


Figure 4. Proportion of organic reactions that require each LO and textbooks that explained the topic related to each LO: most/least acidic/basic atom and equilibrium concepts.

analyzing one reaction, the two researchers compared their codes to ensure consistency in the coding system; after the five reactions were coded, the codes were identical in more than 90% of cases.

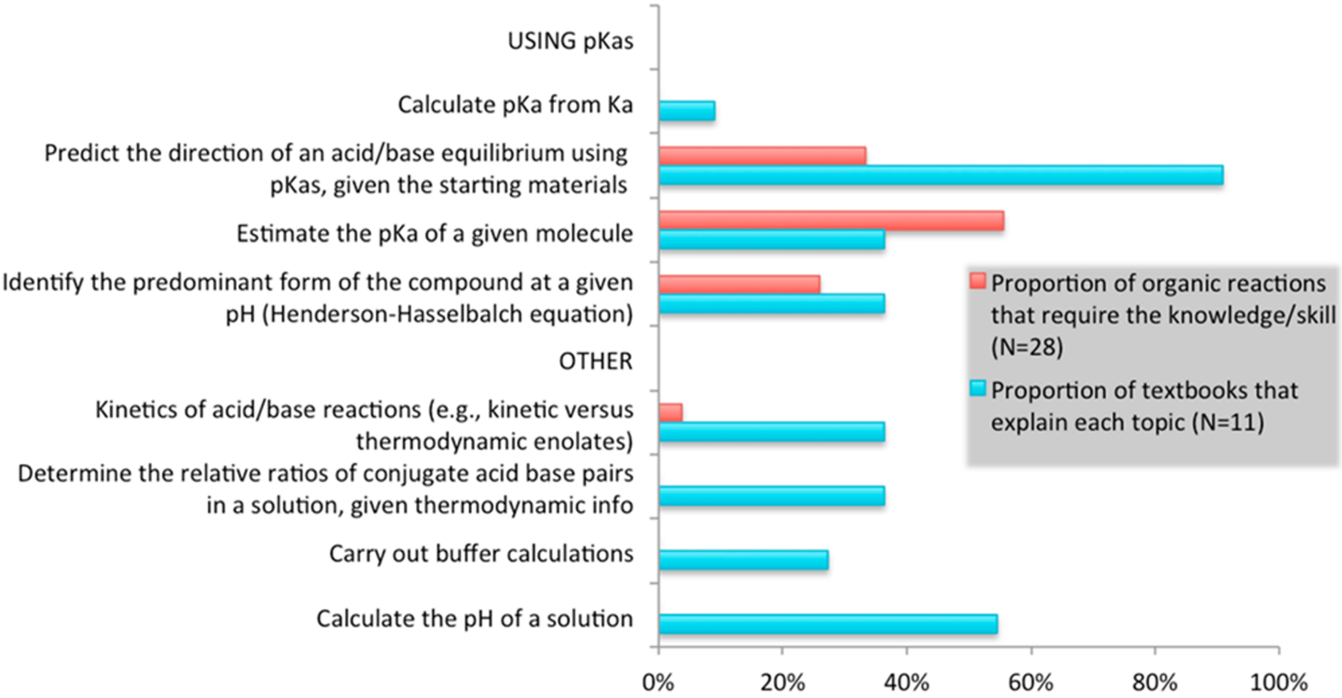


Figure 5. Proportion of organic reactions that require each LO and textbooks that explained the topic related to each LO: pK_a values and "other" LOs.

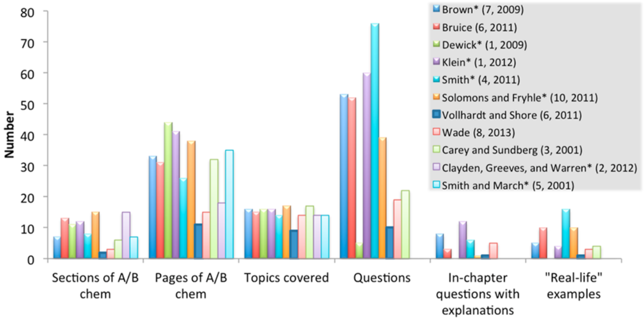


Figure 6. Coverage of acid−base concepts in organic chemistry textbooks. Legend: Author(s) (edition, year); *signifies a textbook with a chapter dedicated to acid−base.

The knowledge and skills required in more than 70% of the reactions analyzed (Figures 3−6) included identifying/drawing a Brønsted acid−base, deprotonating or protonating a molecule, and identifying the most acidic or basic site in a molecule. Those required in more than 30% of reactions included estimating the pK_a of a given molecule, determining the stronger/weaker acid or base using pK_a values or relative base stabilities, being able to use physical factors to explain acidity/basicity (in particular: electronegativity, atom size, resonance, and inductive effects), predicting the direction of an acid−base equilibrium, and drawing a base that could deprotonate a given acid. The LOs that are listed with a "0%" indicate that these LOs were not required in any of the reactions we analyzed, but they related to topics found in some textbook explanations (see below).

The knowledge and skills described in this section relate only to the acid−base steps within more complex reactions. If students have not mastered acid−base concepts, at least 86% of reactions will present difficulties to the students just at the proton-transfer level. One can imagine these difficulties increasing for the other aspects of the reaction and affecting students' abilities to understand or predict the outcome of new reactions.

■ TEXTBOOK COVERAGE OF ORGANIC ACID−BASE TOPICS

Having identified the LOs required to analyze more complex reactions, we looked at the related textbook coverage. We analyzed eight introductory organic chemistry textbooks[27−31] and three advanced organic chemistry textbooks[32−34] to determine how and what topics acid−base chemistry were present (Figures 3−5). We identified whether the "topic" was covered and not the "intended learning outcome" or "learning objective," because none of the textbooks analyzed used the latter terms. Two additional researchers independently coded a random subsample (researcher 2: 7 intro texts, 1 advanced text; researcher 3: 9 intro texts), which resulted in identical coding in over 90% of cases. The details of our analysis can be found in the Supporting Information.

We calculated the amount of acid−base coverage based on the number of pages, sections (subsets of chapters), examples (including "real-life") and questions (subdivided by in-chapter and end-of-chapter questions) dedicated to acid−base chemistry (Figure 6). Although the textbook layout has an effect on the amount of text per page, the textbooks were of approximately the same length (average = 1280 pages, SD = 127 pages), not including Dewick[27] (696 pages) and Smith and March[34] (2083 pages). Figure 6 reveals wide variation in the number of sections, pages, examples, and questions that were explicitly devoted to Brønsted acid−base chemistry. The textbooks had an average of only 2% of the pages explicitly devoted to acid−base chemistry, with the exception of Dewick's textbook,[27] in which over 6% of its 696 pages were devoted to the topic.

Table 1. Intended Learning Outcomes for Introductory Organic Acid–Base Chemistry

Intended learning outcomes	SOLO level	Percentage of professors who deemed the ILO to be essential ($N = 5$)
Definitions		
Identify/Draw an Arrhenius acid/base	2	20
Identify/Draw a Brønsted acid/base	2	100
Identify/Draw a Lewis acid/base	2	100
Mechanism-Related		
Deprotonate a given molecule	2–4	100
Protonate a given molecule	2–4	100
Identify the acid, base, conjugate acid, and conjugate base, given the starting materials	2	100
Draw the conjugate acid and conjugate base (as appropriate), given a molecule	3–4	100
Draw the mechanism of an acid/base reaction, given the starting materials	3–4	100
Draw the result of adding deuterated species	3–4	60[a]
Most/Least Acidic Proton or Most/Least Basic Atom		
Identify the most acidic proton, given a molecule	4	100
Identify the most basic atom, given a molecule	4	100
Given two bases, determine the stronger/weaker of the two using relative base stabilities[b]	4	100
Given two acids, determine the stronger/weaker of the two using relative base stabilities[b]	4	100
Factors to apply: Resonance, electronegativity, inductive effects, size of the basic atom, hybridization, solvent effects, hyperconjugation	3–4	100[c]
Equilibrium Concepts		
Predict the direction of an acid/base equilibrium using relative base stabilities, given the starting materials	4	100
Draw (or select from a list) a base that could quantitatively deprotonate a given acid	5	100
Draw (or select from a list) an acid that could quantitatively protonate a given base	5	100
Identify the strongest acid and base that can exist in water (or a given solvent)	4	100
Using pK_as		
Calculate pK_a from K_a	2	60[d]
Given two acids, determine the stronger/weaker of the two using pK_as	2	100
Given two bases, determine the stronger/weaker of the two using pK_as	3	100
Predict the direction of an acid/base equilibrium using pK_as, given the starting materials	3	100
Estimate the pK_a of a given molecule	2–4	100
Identify the predominant form of the compound at a given pH (Henderson–Hasselbalch equation)	4	100
Other		
Draw the kinetic enolate and identify reaction conditions that could generate it	4	20[a]

[a] The other professors believed this should be learned later. [b] Use the "Factors to apply" row to appropriately compare charges species (bases or acids). [c] Only 40% and 0% of professors surveyed believed that hyperconjugation and solvent effects, respectively, should be learned at this early level. [d] 80% felt that this should have been learned previously.

We found wide variation in the coverage of various acid–base topics, although the textbooks consistently covered Brønsted and Lewis definitions, acid–base mechanisms, and pK_a (although infrequently K_a). All the textbooks covered more acid–base concepts explicitly in later chapters, for example, by explaining kinetic versus thermodynamic enolates. However, connections back to earlier topics were infrequent, such as deciding which oxygen of a carboxylic acid should be protonated during the Fischer esterification.

Less frequently covered topics included determining the position of an acid–base equilibrium either by pK_a or by comparing the relative stabilities of the base and conjugate base (or acid and conjugate acid), pH, and identifying the predominant species at a given pH.

Although the majority of textbooks explained Lewis acids and bases, Brønsted acid–base reactions do not require using the Lewis definition (Figure 3); the Brønsted definition is sufficient in this section, in which students are learning their very first reactions. We link back to Lewis acid–base theory in the next section of the course and correlate it with electrophiles and nucleophiles. Two textbooks explained the Arrhenius definition; although this definition is not essential for organic reactions, addressing the limitations of this definition could be helpful.[2] Many students have learned acid–base chemistry only in the context of aqueous solutions, which generates associated misconceptions.[5,7,8]

Most textbooks explained how to (1) protonate or deprotonate a given molecule, (2) draw the mechanism of acid–base reactions, and (3) draw the resulting conjugate acid and base (Figure 3). These skills are essential for all more complex organic mechanisms that have acid–base steps.

The majority of textbooks also explained how to determine the strongest acid or base and use that information to determine the direction of acid–base equilibria (Figure 4). However, less than half explained how to identify the most acidic or basic atom within a molecule. Although these are closely related concepts, in our experience, many students struggle to see that relationship. Approximately one-third of the organic reactions we analyzed required making a choice of an appropriate acid or base (e.g., the choice of base to generate an organolithium reagent); only two textbooks explained how to do this. Related to equilibrium concepts is figuring out what the strongest acid or base is that can exist in a given solvent; approximately 16% of reactions and textbooks required and explained, respectively, how to do so.

The factors that control relative base strength and those most often needed to analyze complex reactions were also the ones most commonly explained in textbooks (i.e., resonance,

Table 2. Outline of the SOLO Taxonomy and Verbs Commonly Associated with Each Level[23]

SOLO Level	At this level, the student:	Associated verbs
1: Prestructural	Shows little evidence of learning	Uses irrelevant information, misses the point, avoids the question
2: Unistructural	Deals with terminology, uses one single aspect without making connections.	Identify, define, recall, name, follow simple procedure
3: Multistructural	Deals with several aspects, but does not make connections between them.	Enumerate, describe, list, combine, do algorithms
4: Relational	Makes connections between several aspects and how they fit together. The student has increased competence.	Compare/contrast, argue, solve, explain causes, analyze, relate, apply
5: Extended abstract	Goes beyond what was given, analyzes concepts from different perspectives, and transfers ideas to new areas.	Theorize, generalize, hypothesize, create, reflect

electronegativity, inductive effects, and size of the basic atom) (Figure 4). Factors less frequently encountered were also less frequently explained (i.e., hybridization, solvent effects, and hyperconjugation). Three textbooks explained deuterated acids and bases; although the use of deuterium is relevant in many areas, including kinetic studies and spectroscopy, this aspect could be taught later—when it is immediately relevant.[35]

More than 80% of textbooks explained how to predict the direction of an acid−base equilibrium using pK_a values (Figure 5). Less than 40% explained how to estimate a pK_a when not found in a table or how to identify the predominant form of a compound at a given pH. The latter concept, which uses the Henderson−Hasselbalch equation, is particularly important in biological applications and also for reactions such as amide bond formation.

Two textbooks addressed common errors and misconceptions. Wade[31] explicitly addressed the common misconception regarding identifying a species as being an acid or a base depending on its reacting partner, and not only on the presence of hydroxide and hydronium ions.[10] Solomons and Fryhle addressed the misconception that acid−base reactions only take place in aqueous solution.[30] Many of the misconceptions addressed stem from potential model confusion between the three definitions of acids and bases and differentiating between Arrhenius and Brønsted definitions.

The analysis of textbook topics informed the development of the ILOs described below.

■ INTENDED LEARNING OUTCOMES

Table 1 shows the ILOs we developed following our analysis of more complex reactions and numerous textbooks (our first version is available in the Supporting Information). The intent is that students master these ILOs by the end of the acid−base section in their first organic chemistry course. To be successful, students need to have already mastered concepts and skills such as drawing Lewis structures, line structures, formal charge, electronegativity, resonance, and the electron-pushing formalism (i.e., curved mechanistic arrows). Students who have difficulties with those concepts and skills will likely also have difficulty in the acid−base section. In this study, we did not look at the type of knowledge and skills needed when working in the lab or in other fields related to chemistry, and so this list of ILOs should not be considered as absolute recommendations for instruction.

We organized Table 1 in the approximate order in which each topic is taught. The order of instruction is grounded in scaffolding theory,[36] in which the progression to a desired goal (e.g., learning acid−base chemistry) is simplified and the learner is provided with supports—such as a template—that help the student learn the requisite knowledge or skills in a stepwise fashion. Those supports are removed as the learner gains proficiency. Scaffolding theory recognizes that prior learning impacts future learning by helping learners accomplish tasks within their “zone of proximal development,”[37] an area between what the learner currently knows and can do and does not know or cannot do at all, where they can work with guidance.

Brønsted acid−base chemistry is taught first and in most detail (Lewis acid−base theory not addressed until later in the course). Next, students learn to draw the mechanism of acid−base reactions using the electron pushing formalism learned in the previous module of the course,[38] as well as terminology (e.g., protonate, deprotonate, conjugate acid, conjugate base). We teach students how to compare the relative stability of bases using the factors listed in the table to determine the strongest or weakest base between two or more molecules or within a single molecule (i.e., identify the most basic atom). They also use those factors to identify the strongest acid in a set or within a molecule (most acidic proton), usually by drawing the conjugate base first. Those skills are acquired before students learn to use pK_a values, so that they learn the reasons behind the pK_a values.

Students then learn equilibrium concepts, still without the use of pK_a values, and after that, the use of pK_a values with organic molecules is taught. Estimating the pK_a of a given molecule could be as simple as finding the exact molecule in a table (SOLO 2), having to approximate it based on the most similar functional group in the simplified pK_a table we provide (SOLO 3), or approximating the pK_a values of a series of closely related molecules, such as *para*-methoxyphenol, *meta*-nitrophenol, and *para*-nitrophenol (pK_a values in water: 10.20, 8.35, and 7.14, respectively).[39] The relationship between pH and pK_a is addressed and a link is made to biochemistry (e.g., amino acids).

Every time a new chemical reaction is learned that includes an acid−base step, the relevant aforementioned knowledge or skills are explicitly revisited.

The structure of the ILOs was primarily based on the Structure of Observed Learning Outcomes taxonomy (SOLO)[23] and also aided by the cognitive domain of the modified Bloom taxonomy.[40] The SOLO taxonomy (Table 2) describes “how a learner’s performance grows in complexity when mastering many academic tasks.”[23] In the prestructural level, SOLO 1, there is little evidence of learning. At the unistructural level, SOLO 2, the student learns quantitative information, deals with declarative knowledge such as terminology, and uses one single aspect without making connections. At the multistructural level, SOLO 3, the student continues learning quantitative information and declarative knowledge, and can deal with several aspects, but does not make connections between them. At the relational level, SOLO 4, the student’s competencies have increased and become qualitative as well as quantitative. The student can make connections between several aspects or concepts and demonstrate how they fit together. At the extended abstract level, SOLO 5, the student goes beyond the information and explanations that were explicitly provided. The student's abilities include being able to analyze concepts from different perspectives, generalize, create, and transfer ideas to new areas.

We assigned SOLO levels to each ILO;[23,41] some ILOs have a range of SOLO levels, depending on the context. For example, deprotonating water requires only a simple procedure (SOLO 2), whereas deprotonating a complex molecule like taxol requires analyzing multiple acidic protons, and comparing them (or their conjugate bases) to determine which is most acidic (SOLO 4).

ILOs should also be specific, measurable, achievable, relevant, and timely, or "SMART," an acronym that has been used in sport,[42] business,[43] and education[44,45] to promote the development of useful goals. A **specific** LO states exactly what needs to be done or known and to what level (e.g., degree of difficulty). A **measurable** LO uses a verb that results in an outwardly visible or demonstrable LO.[23,40,45−47] For example, a student's drawing is visible, while a student's appreciation or understanding of a topic is not. Thus, the former results from a measurable verb (draw), whereas the latter does not (appreciate or understand). An **achievable** goal is appropriate to the learner's stage of development and can be accomplished in the allotted time frame. An LO can be **relevant** because it is required for the next stage of learning. Some topics that are taught in textbooks, such as buffers and pH calculations, were omitted from the list of ILOs because they are not relevant for our organic chemistry courses. **Timely** (or time-bounded) LOs provide the time frame for the learner. For example, students should master these acid−base LOs by the end of the acid−base module in the first organic chemistry course.

■ EXPERTS' OPINIONS

Having developed a list of intended learning outcomes, we next surveyed organic chemistry professors ($N = 5$). They were asked to identify the LOs they deemed essential for mastery by the end of the second course in organic chemistry and to add any others (Table 1). There was consensus that most of the LOs were essential, and there were some differences of opinion for a few LOs. Most professors felt that the Arrhenius definition was unimportant, although one felt that it should be taught for the purpose of emphasizing that water is not necessarily the solvent. Most thought that some concepts should have been learned in other courses and so were not important as organic chemistry LOs, such as buffer and pH calculations (consequently omitted from Table 1). According to most of the professors surveyed, some concepts should be left to more advanced courses, including solvent effects, kinetic versus thermodynamic enolates, and deuteration. We aligned the course's learning activities and assessments with the LOs deemed most important and the known student difficulties. This process is described next.

■ ASSOCIATED LEARNING ACTIVITIES

Most of the learning activities associated with the ILOs require simply adding a molecular structure to the ILO statement. The choice of compound, however, can allow misconceptions and common error to be addressed, which often affects the SOLO level. Examples of questions are shown in Figure 7.

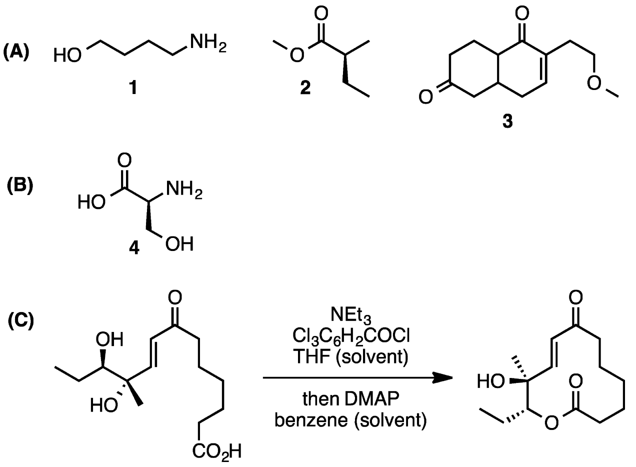


Figure 7. Examples of questions: (A) Protonate each compound at its most basic site. (B) Draw the predominant species at pH 7. (C) Draw the reaction mechanism and justify your answer.

For example, if students are asked to protonate a given molecule, they could be given methanol as an example, which could be considered SOLO 2 because it requires following a straightforward procedure. To incorporate multivariate thinking (e.g., getting past the concept that resonance does nothing but stabilize molecules) and access higher SOLO levels, more functionalized structure could be provided (Figure 7, compounds 1−3). The focus on base strength addresses the lack of familiarity with bases.[14]

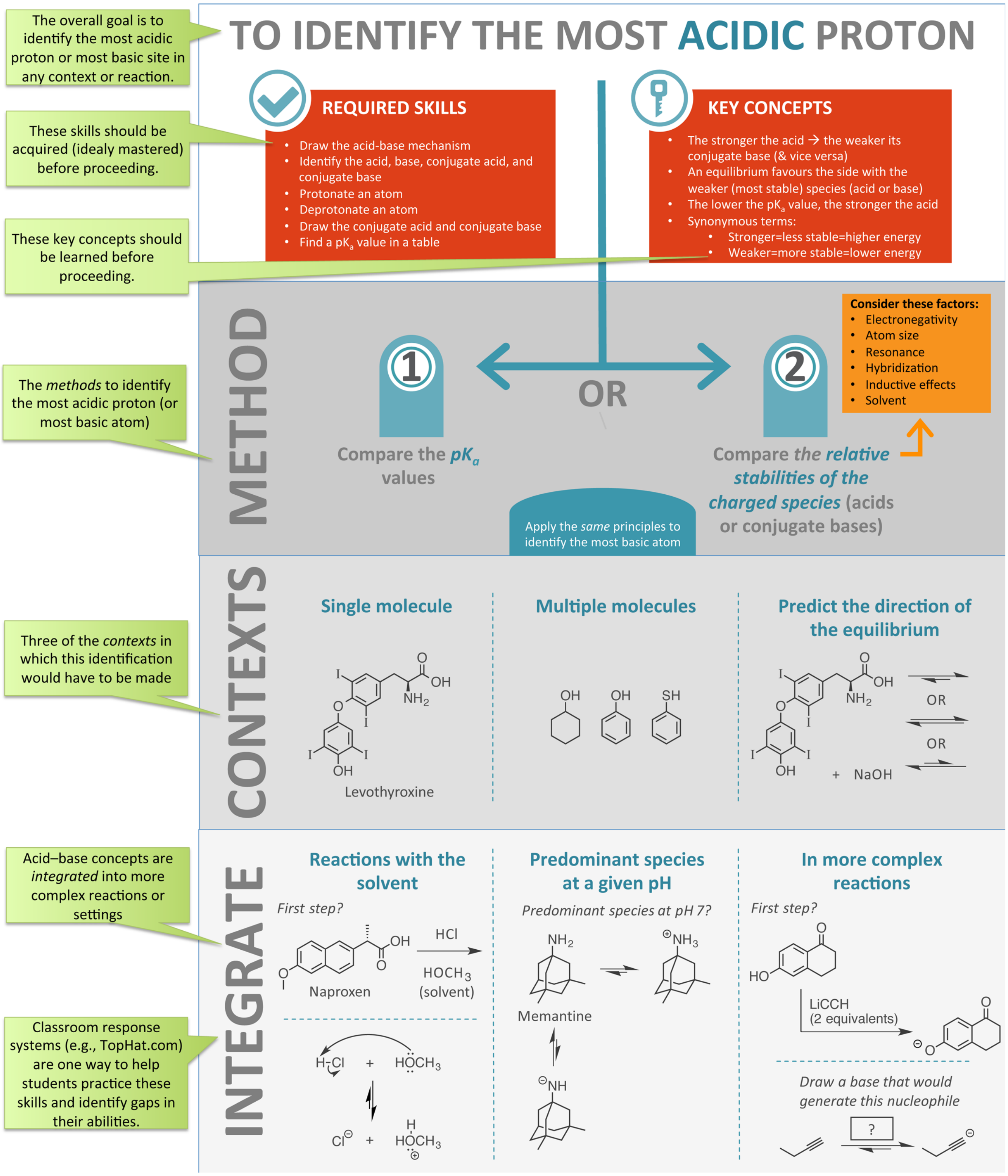
A second question (Figure 7B) asks students to identify the predominant species at pH 7; this provides opportunities to address the difference between pH and pK_a,[19] as well as revisit discussions of acid−base equilibria, mechanisms, pK_a, and more.

The third question (Figure 7C) situates an acid−base question within a more complex reaction—the Yamaguchi macrolactonization.[25,48] In this question type, students can be asked to explicitly connect back to previously learned acid−base concepts. To answer the question, students must identify the most acidic proton and the base in the starting materials, decide whether to deprotonate the substrate in the first step, and could also be asked how to extract the final product from the reaction mixture (which would require determining the predominate species at various pH values, considering solubility, and equilibria).

Another question (not shown) could ask students to decide whether a substance is an acid, a base, or both, and to justify their answer. Acetic acid is typically used for this purpose first as an in-class question. This question addresses the misconception that a substance can always be defined as either an acid or as a base;[14] by asking students to justify their answer, they must consider what compounds would react with the one provided to make it act as an acid in one case and a base in another.

These types of learning activities can be formulated as classroom response system (clicker) questions, assignment questions, and can also be used as assessment questions. The list of ILOs can serve as a checklist to make sure learning opportunities and assessments have been created for every expected LO and then as a way to monitor students' progress toward the intended outcomes.

These LOs were initially communicated to students via a list that resembled Table 1. However, we found that students could



The overall goal is to identify the most acidic proton or most basic site in any context or reaction.

TO IDENTIFY THE MOST ACIDIC PROTON

These skills should be acquired (idealy mastered) before proceeding.

REQUIRED SKILLS

- Draw the acid-base mechanism
- Identify the acid, base, conjugate acid, and conjugate base
- Protonate an atom
- Deprotonate an atom
- Draw the conjugate acid and conjugate base
- Find a pK_a value in a table

These key concepts should be learned before proceeding.

KEY CONCEPTS

- The stronger the acid → the weaker its conjugate base (& vice versa)
- An equilibrium favours the side with the weaker (most stable) species (acid or base)
- The lower the pK_a value, the stronger the acid
- Synonymous terms:
  - Stronger=less stable=higher energy
  - Weaker=more stable=lower energy

The *methods* to identify the most acidic proton (or most basic atom)

METHOD

1 Compare the pK_a values

OR

2 Compare *the relative stabilities of the charged species* (acids or conjugate bases)

Consider these factors:

- Electronegativity
- Atom size
- Resonance
- Hybridization
- Inductive effects
- Solvent

Apply the *same* principles to identify the most basic atom

Three of the *contexts* in which this identification would have to be made

CONTEXTS

Single molecule

Multiple molecules

Predict the direction of the equilibrium

Acid–base concepts are *integrated* into more complex reactions or settings

Classroom response systems (e.g., TopHat.com) are one way to help students practice these skills and identify gaps in their abilities.

INTEGRATE

Reactions with the solvent

First step?

Predominant species at a given pH

Predominant species at pH 7?

In more complex reactions

First step?

Draw a base that would generate this nucleophile

Figure 8. Educational graphic to guide students through the intended learning outcomes. Available with explanatory videos at http://mysite.science.uottawa.ca/aflynn/Organic_Acid-Base.html.

only use the list when directly provided with associated questions (as shown in the Supporting Information); they did not know how to make use the learning outcomes (e.g., to identify a missing skill when they were presented with a problem on its own). Thus, we created a type of learning outcome graphic that more visually depicts and breaks down the required elements (Figure 8). Overall, the goal is to be able to identify the most acidic proton or most basic atom in various contexts. Before doing so, students should have mastered the required skills and key concepts (red boxes). They can use either Method 1—comparison of pK_a values—or Method 2—comparison of relative stabilities of the charged species (using the factors in the orange box)—to identify the most acidic or basic site in the three contexts listed. Once they have gained skill in those isolated contexts, they can integrate their skills into more complex reactions (examples provided in the bottom section). This graphic is available with associated explanatory videos on the corresponding author's homepage (http://mysite.science.uottawa.ca/aflynn/Organic_Acid-Base.html).

■ CONCLUSIONS

We developed a comprehensive set of intended learning outcomes (ILOs) for organic Brønsted acid−base chemistry and transformed what we assessed to be the most essential ones into an an educational graphic (Figure 8). To do so, we analyzed more complex organic reactions, on the topics covered in textbooks and on known student difficulties. These ILOs were classified using the SOLO taxonomy and were communicated with students. They guide our courses' teaching and learning activities and are used to create assessments.

Future work will involve surveying practicing chemists and those working in related fields to determine the organic acid−base knowledge and skills required in their daily practice using an instructional design model that has been used in other studies.[49,50] We will also study students' learning gains associated with the intended learning outcomes described here.[51]

We highlighted the prevalence of acid−base reactions in more complex organic chemistry contexts and emphasized the need for student mastery of the related concepts and skills. We hope that the learning outcomes, educational graphic (Figure 8), and examples of aligned questions will be useful for educators and students.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Contains the full analysis of (1) identification of acid−base processes present in other reactions; (2) the amount and topics covered by textbooks; and (3) an early version of the organic acid−base intended learning outcomes before analysis of organic reactions and textbooks. This material is available via the Internet at http://pubs.acs.org.

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Notes

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