

# Why and How To Teach Acid–Base Reactions *without* Equilibrium

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Acid–base reactions are important. They cause dramatic changes in solubility, volatility, interphase partitioning, molecular association, and reactivity. Applications of these changes include synthesis, separation, dyeing, and protein denaturation.

Yet acid–base reactions receive scant attention in introductory chemistry courses and textbooks. To be sure, acids, bases, and pH are invariably defined. Acid dissociation constants are commonly introduced as measures of acid strength, and considerable time may be devoted to equilibrium calculations. But the reactions themselves are introduced ad hoc and receive little attention in their own right, either before or after the treatment of acid–base equilibria.

In contrast, reactions are the focus of my own presentation of acids and bases in first-semester college chemistry. I teach students to predict acid–base reactions before introducing anything about equilibrium. The key to doing this is to treat each reaction as either going to completion or not occurring at all.

What advantages does this all-or-none approach have over an equilibrium one? The all-or-none approach is ideally suited to keeping track of the dominant species and their charges under various conditions. Acid–base reactions change these charges by addition or removal of  $H^+$ , thereby affecting solubility and other previously mentioned properties. There is a danger that prior or concurrent attention to equilibrium may complicate acid–base reactions unnecessarily for beginning students, particularly because of the mathematical difficulty of equilibrium calculations. In the all-or-none approach, the only quantitative aspect is stoichiometry, and even that is invoked only if one needs to identify which reactant is in excess.

In addition, the all-or-none approach should help students succeed when they later study equilibrium. Consider, for example, the problem of calculating equilibrium concentrations after acetic acid and sodium hydroxide are mixed. Choices of equilibrium-constant expression and of initial concentrations depend on the fact that the reaction goes essentially to completion, as well as on which reactant is in excess. A student who cannot handle these preliminary matters with facility is handicapped in dealing with equilibria of even modest complexity.

## Method

The present method uses the same sequence of steps to solve all acid–base reaction problems, no matter how complicated the chemical system. This method promotes active thinking rather than rote learning. The solving of each problem starts with what is known about the chemical system and involves the following steps *in order*:

1. Identify compounds that dissociate in solution.
2. List the major species.
3. Classify these species as acids and bases.
4. Identify the strongest acid and the strongest base.

5. Decide whether these two species can react.
6. If they react, write the equation for the reaction.
7. Repeat steps 2–6 until no further reaction can occur.

I will now summarize for each of these steps the instructions that I give students for predicting reactions in aqueous solution.

*Identifying compounds that dissociate.* Memorize the important strong acids  $H_2SO_4$ ,  $HNO_3$ ,  $HCl$  (and  $HBr$  and  $HI$ ). Assume that any other acid is weak unless you are told that it is strong. In water, every strong acid dissociates completely to its conjugate base and  $H_3O^+$ . Soluble salts, oxides, and hydroxides dissociate completely to their cations and anions.

*Listing species.* The list of major solute species consists of formulas of the compounds that do not dissociate and formulas of the ions formed by the compounds that dissociate completely. Omit from the list the products of the slight reaction between water and a weak acid or base. Also recognize that the strong bases  $O^{2-}$  and  $S^{2-}$  react completely with water. In their place, list the products of those reactions:  $O^{2-}$  forms  $OH^-$ , whereas  $S^{2-}$  forms both  $SH^-$  and  $OH^-$ .

*Classifying species.* Recognize the following as acids:

- Formulas beginning with H
- Formulas containing  $-COOH$
- $NH_4^+$  and (optionally) conjugate acids of amines

Recognize the following as bases:

- Anions *except* conjugate bases of strong acids
- $NH_3$  and (optionally) amines

An amphiprotic species, such as  $HCO_3^-$ , is both an acid and a base.

*Identifying the strongest acid and base.* I provide an expanded version of Table 1, which lists acids and conjugate bases in order of their strengths. This table is much like ones advocated by Treptow (1). The order of strengths is reversed, however, to match the order of acid strengths found in most wall charts and textbook tables. In addition, brackets indicate acids of similar strength.

*Deciding whether this acid and base can react.* The strongest acid and the strongest base react first. The reaction occurs if the acid is higher than the base in Table 1. If the acid and base are within the same pair of brackets, then the reaction goes only part way to completion. The strong acid  $H_3O^+$  is sure to react with the base even if the base does not appear in the table. Likewise  $OH^-$  will react with any acid.

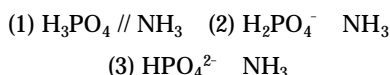
I justify the table-based criterion for reaction by an extended explanation of conjugate acids and bases. This culminates with a proof that the products of any spontaneous acid–base reaction are a weaker acid and weaker base than the reactant acid and base, respectively. To make this pre-

sensation convincing and enjoyable, I use magnets to represent bases of different strengths, as described by Naylor and Blackman (2).

An ordered list of strengths like Table 1 enables students to predict acid–base reactions without any knowledge of equilibrium. I prefer to teach acid–base reactions before equilibrium, but if instead acid dissociation constants had already been introduced, then the table could have listed  $K_a$  values instead of bracketing certain acids. The reaction goes over 99% of the way to completion if  $K_a$  for the reactant acid is more than 100 times as large as  $K_a$  for the conjugate acid of the reactant base.

*Writing the equation.* Stop with the transfer of one proton. The products are the conjugate base of the reactant acid and the conjugate acid of the reactant base.

*Repeating steps 2–6.* The novel feature is to update the list of species by eliminating the limiting reactant and adding products of the preceding reaction. (Nothing is lost by omitting nonamphiprotic products from the new list.) For example, in predicting reactions that occur when phosphoric acid is added to a large excess of ammonia solution, the successive sets of species to be considered would be:



(I use a pair of slashes to separate species in different solutions. This emphasizes the fact that the first reaction after mixing is between a species from one solution and a species from the other.) Table 1 shows that  $\text{H}_3\text{PO}_4$  and  $\text{H}_2\text{PO}_4^-$  can

**Table 1. Acids and Bases in Order of Their Strengths<sup>a</sup>**

Strongest acid	Weakest base
$\text{H}_3\text{O}^+$	$\text{H}_2\text{O}$
$\text{H}_2\text{C}_2\text{O}_4$	$\text{HC}_2\text{O}_4^-$
$\text{SO}_2 + \text{H}_2\text{O}$	$\text{HSO}_3^-$
$\text{HSO}_4^-$	$\text{SO}_4^{2-}$
$\text{H}_3\text{PO}_4$	$\text{H}_2\text{PO}_4^-$
$\text{HNO}_2$	$\text{NO}_2^-$
$\text{HF}$	$\text{F}^-$
$\text{HC}_2\text{O}_4^-$	$\text{C}_2\text{O}_4^{2-}$
$\text{CH}_3\text{COOH}$	$\text{CH}_3\text{COO}^-$
$\text{CO}_2 + \text{H}_2\text{O}$	$\text{HCO}_3^-$
$\text{H}_2\text{S}$	$\text{HS}^-$
$\text{H}_2\text{PO}_4^-$	$\text{HPO}_4^{2-}$
$\text{HSO}_3^-$	$\text{SO}_3^{2-}$
$\text{HCN}$	$\text{CN}^-$
$\text{NH}_4^+$	$\text{NH}_3$
$\text{HCO}_3^-$	$\text{CO}_3^{2-}$
$\text{H}_2\text{O}_2$	$\text{HO}_2^-$
$\text{HPO}_4^{2-}$	$\text{PO}_4^{3-}$
$\text{H}_2\text{O}$	$\text{OH}^-$
Weakest acid	Strongest base

<sup>a</sup>Species of nearly equal strengths are bracketed together.

react with ammonia but  $\text{HPO}_4^{2-}$  cannot.

### Simple Example Problem

What is the first reaction, if any, when hydrochloric acid is added to a solution of ammonia and ammonium fluoride?

#### Problem Solution

Solute species:  $\text{H}_3\text{O}^+$   $\text{Cl}^-$  //  $\text{NH}_3$   $\text{NH}_4^+$   $\text{F}^-$   
 Classification: acid    neither    base    acid    base  
                                  strongest                                   strongest

This reaction does occur:  $\text{H}_3\text{O}^+ + \text{NH}_3 \rightarrow \text{H}_2\text{O} + \text{NH}_4^+$ .

### Quantitative Multireaction Example Problem

Calculate concentrations of all solute species that remain after 300 mL of 0.30 M potassium carbonate is mixed with 200 mL of a solution that is 0.15 M in  $\text{HNO}_2$  and 0.20 M in  $\text{H}_2\text{S}$ .

#### Problem Solution

Solute species:  $\text{K}^+$   $\text{CO}_3^{2-}$  //  $\text{HNO}_2$   $\text{H}_2\text{S}$   
 Classification: neither    base    acid    acid  
                                  strongest    strongest

FIRST REACTION:  $\text{CO}_3^{2-} + \text{HNO}_2 \rightarrow \text{HCO}_3^- + \text{NO}_2^-$   
 Moles before reaction: 0.090    0.030    0.000    0.000  
 Moles after reaction: 0.060    0.000    0.030    0.030

Now repeat the process to decide what reaction would occur next.

Solute species:  $\text{CO}_3^{2-}$   $\text{H}_2\text{S}$   $\text{HCO}_3^-$   $\text{NO}_2^-$   
 Classification: base    acid    acid and base    base  
                          strongest    strongest

SECOND REACTION  $\text{CO}_3^{2-} + \text{H}_2\text{S} \rightarrow \text{HCO}_3^- + \text{HS}^-$   
 Moles before: 0.060    0.040    0.030    0.000  
 Moles after: 0.020    0.000    0.070    0.040

Now update the species and consider the possibility of further reaction. (Because  $\text{HS}^-$  is the conjugate acid of the strong base  $\text{S}^{2-}$ ,  $\text{HS}^-$  is not classified as an acid.)

Solute species:  $\text{CO}_3^{2-}$   $\text{HCO}_3^-$   $\text{NO}_2^-$   $\text{HS}^-$   
 Classification: base    base and acid    base    base  
                          strongest                                   strongest

No further reaction can occur. Concentrations in the 500 mL mixture are:

$\text{K}^+$   $\text{CO}_3^{2-}$   $\text{HCO}_3^-$   $\text{NO}_2^-$   $\text{HS}^-$   
 0.36 M    0.040 M    0.140 M    0.060 M    0.080 M

### Discussion and Generalization

This method of predicting acid–base reactions involves

a sequence of questions. The essence of this sequence is the hierarchy *first things first*. What species are present? Which if any are acids and bases? Are at least one acid and one base present? Which is the strongest acid, and which is the strongest base? Can they react together? If the answer to certain of these questions is negative, the problem is solved with the answer "No reaction", and subsequent questions need not be asked. This efficiency in eliminating reactions is particularly important for situations in which the species might also react in ways other than acid–base.

I point out to students some advantages of this sequence. The same questions are asked, no matter how complicated the reaction mixture. The questions lead naturally to one another, and skipping a question or asking it out of order entails risks. A major advantage is that one can focus attention at each stage on the small number of matters pertinent to that question rather than being distracted by the confusing abundance of facts and principles that might bear on the problem as a whole.

Adherence to this sequential method increases greatly the likelihood of solving problems correctly. Success contributes to students' self-confidence and their satisfaction with chemistry, and so does the feeling that they understand *why*

the method works. Furthermore, the method is general. It is easier and more satisfying to learn a single method capable of handling all acid–base reactions than to learn a multiplicity of methods for special cases. Efficiency, success, clarity, generality—this method has many advantages.

This method lays a sound foundation for subsequent topics in reaction chemistry. The listing and classifying of species is a good way to begin any search for possible reactions. The sequence of questions is readily adapted to other types of reactions. In organic chemistry, for example, one also asks: What functional groups are present? In the context of oxidation–reduction reactions, one asks: Are at least one oxidizing agent and one reducing agent present?

Wherever possible, we should promote problem-solving methods that divide complicated problems into manageable steps and that address first things first. At stake is not just whether students will solve problems correctly, but how rapidly and fully they become autonomous askers of their own questions.

#### Literature Cited

1. Treptow, R. S. *J. Chem. Educ.* **1986**, *63*, 938–941.
2. Naylor, R. W.; Blackman, D. *J. Chem. Educ.* **1981**, *58*, 1017.