TABLE 1

Hypothetical learning progression for acid-base chemistry.

	Before general chemistry	After general chemistry	After organic chemistry	After biochemistry
Students should:				
pH and pKa	(May) be familiar with pH scale and associate it with acid/base (May) know pH scale is from 0–14 and < 7 is acidic, 7 neutral, > 7 basic	Know pH scale is from 0–14 and < 7 is acidic, 7 neutral, > 7 basic Can convert between [H+] and pH [OH-], and pOH (pH + pOH = 14, pH = -log[H+]) Recognize that pH scale is log, and difference between whole units is 10x Recognize that pH scale is ratio between H+/OH- Know pKa is the –logKa, and the < the pKa, the stronger the acid	Know general trends of pKas by structures and estimate pKas of groups Predict direction of equilibrium given pKas	Can predict ionization states from pKa/pH relationship Predict function as a result of structure due to pH (rxn mechanism of enzymes) Predict stability and solubility as a result of structure due to pH environment (folding, IMFs) Know of microenvironment as it relates to pH and pKa (enzyme active site pockets)
Acid/base models	Define by Arrhenius model and see acids as containing H^+ and bases as containing OH^- Will describe A/B by macroscopic stereotypes: acid is red and sour, base is blue and bitter	Define A/B by Bronsted-Lowry model and see acids as H^+ donors and bases and H^+ acceptors Recognize Lewis model and see acids as e acceptors and bases as e donors	Bronsted-Lowry H^+ movement and Lewis model electro/nucleophiles	N/a
Ionization	n/a	Able to identify conjugate pairs, protonate and deprotonate, but without mechanism Able to define strong /weak acid/ base (fully dissociates, etc.) but difficulty identifying/ recognizing examples beyond periodic trends and memorization Know that the stronger the acid, the weaker the conjugate base, and vice versa Can define a polyprotic acid, but may not be able to identify one	Able to identify conjugate pairs, protonate and deprotonate with arrow pushing mechanism Identify strongest/weakest acid/base from structure through periodic trends, electronegativity, inductive effect, resonance, etc. Identify strongest acid/ base that can exist in given solvent Pick acid/base to protonate/ deprotonate a given group Can identify and predict action/mechanism of polyprotic acids	Understand ionization as it applies to a population of molecules Predict structure due to ionization (protonate/ deprotonate, effects on IMFs)
Equilibrium, Buffers, Henderson-Hasselbalch	Think equilibrium is when there are equal amounts of species in a solution Think of buffers in only abstract terms: it "absorbs," "acts like a sponge" Think buffers maintain a solution at pH 7	Know that chemical reactions are reversible Know that equilibrium is when the forward and reverse reactions occur at equal rates Can define Le Chatelier's principle Predict change to a system as a product/reactant are added at equilibrium (apply Le Chatelier's principle) Predict the direction of equilibria given starting materials Can define buffers as solutions of weak acid & conj. base (in ~equal concentrations) that resist change to pH Know Henderson-Hasselbalch equation and can apply it, but may not be able to explain it	Identify the predominant ionization form given pH using the HH eq.	Understand how shifts to equilibrium affect behavior Understand effects of open and closed systems and able differentiate between them Make, explain, and choose appropriate buffers, including buffer strength/ capacity Can employ and explain the HH eq. for any variable

Sources

Before general chemistry: Calatayud et al. (2007); Lin & Chiu (2007); Bernholt & Parchmann (2011); Pan & Henriques (2015); NGSS Lead States (2013).

After general chemistry: Banerjee (1991); Watters & Watters (2006); Romine et al. (2016); Cooper et al. (2016); Cartrette & Mayo (2011); Orgill & Sutherland (2008).

After organic chemistry: Cooper et al. (2016); Stoyanovich et al. (2014); Cartrette & Mayo (2011); Orgill & Sutherland (2008); American Chemical Society (n.d.); McClary & Talanquer (2011); Tümay (2016)

After biochemistry: Orgill & Sutherland (2008); American Chemical Society (2015); Villafañe et al. (2011); Berg et al. (2002); Nelson & Cox (2008); Voet et al. (2004); American Society for Biochemistry and Molecular Biology (n.d.).