Guidelines for the "pH Quest" assignment

Work on the assignment as a group. Discuss questions. Brainstorm ideas.

However, during the duration of the study, do not share questions/answers to the problems with any of the classmates outside of your group. You also promise to not use cellphones/books/lecture notes/internet when working on this project. You are allowed to use a calculator and a periodic table.

Write answers in such a way that you can always justify them if asked. You may be "audited" for some of your answers. If you discovered something new for yourself, make a note.

Do not skip questions, answer them one by one.

You have to answer every single question in a given level before receiving opening up new levels. In total, there are 6 levels. You have to clear them all in order to **receive the credit** – 20 points.

When finished with a level, submit your work to your instructor or TA.

They will either accept it as correct (and give new level assignments) or:
- tell how many assignments in a particular level are incorrect (no loss of points)
- if you choose to, tell which particular assignments are incorrect (-5% of the total credit in the end).
- if you choose to, will hint which direction to move to solve an assignment (-5% of the total credit in the end, per every hint)

You may take breaks in between levels (come next day, for example). All of your group members have to be engaged though.

The challenge needs to be solved by xxx. Best wishes!

Names of people in your team	Sign if you acknowledge to follow the guidelines

You will need to bring back all the handouts by the end of this study.

Guidelines distributed before the quests.

Level	Cleared? (attempts)	Penalty (if any)	Initials (instructor or TA)
1 Equilibria			
2 Acids and Bases			
3 Strong and Weak			
4 pH intro			
5 pH and concentration			
6 pH of salts			

Guidelines distributed before the quests.

Equilibria in water.

The simplest and smallest ion, a **proton** (H^+), is not only present in a lot of chemicals, but is commonly thrown from one substance (such are called **acids**) to another (such are called **bases**). An acid, after losing a proton, is called a conjugate base (since it gains the capacity to accept the proton back). A base, after gaining a proton, is called a conjugate acid (since it gains the capacity to give it away).

SIMULATION pHET/introduction/water views: molecules, click on solvent, water in our case

Assignment 1-1.

What are roles of the species involved in this equilibrium?

$$H_2O \quad + \quad H_2O \quad = \quad H_3O^+ \quad + \quad OH^-$$

Assignment 1-2. Write the expression for K for this reaction (remember that liquids and solids are not included in equilibrium expressions). Given amounts of substances at equilibrium (each molecule represents 0.00000005 or 5×10^{-8}M) in equation above, calculate the value of K for the reaction above.

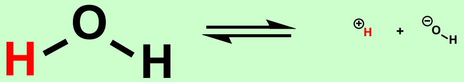
Assignment 1-3. Regardless of whether we deal with a little bit or with a lot of pure water, whether this water is at room temperature or near boiling (for this reaction, K increases with temperature), whether the reaction prefers starting materials or products (the illustration implies that the equilibrium strongly prefers starting materials), what do you predict for a ratio of $[H_3O^+]$ to $[OH^-]$ in pure water?

Answer:

Three choices. Solutions where $[H_3O^+]>[OH^-]$ are called acidic. Solutions where $[H_3O^+]=[OH^-]$ are called neutral. Solutions where $[H_3O^+]<[OH^-]$ are called basic.

Fixing a misconception. In the paragraph above, do you see any particular pH value (like 7) tied in to acidity/neutrality/basicity? Hopefully not.

Fixing a misconception. In many books, the same equation is written as:



While it looks simpler (and that's why it is commonly used), this equation can be misleading for non-scientists. It suggests that a naked proton is generated which is highly unlikely (too unstable). Scientists that write this equation always imagine "ghost" water molecules surrounding the proton (essentially turning it into H_3O^+ which makes this equation identical to the first one). As a result, whenever you see $[H^+]$ or $[H_3O^+]$ – it refers to the same species, proton surrounded by water. As such, numerically, $[H^+]$ and $[H_3O^+]$ will always have the same value, use them interchangeably

Assignment 1-4.

Look also at (in all cases, click on solvent, water in our case):

SIMULATION pHET/introduction/strong acid

SIMULATION pHET/introduction/weak acid

SIMULATION pHET/introduction/strong base

SIMULATION pHET/introduction/weak base

Write equations and assign roles of all species involved in these four processes. Given amounts of all substances in these processes (each molecule represents 0.00000005 or 5×10^{-8}M), calculate the K for every process.

Strong acid HA:

Weak acid HA:

Strong base MOH:

Weak base B:

Assignment 1-5. What is the fundamental difference between strong and weak acids? Write an explanation for future students – what does it mean for the acid to be weak? What does it mean for the acid to be strong?

Fixing Misconceptions

Students commonly write:

- strong acids are the corrosive ones.

Assignment 1-6. Do you agree with this statement based on your answer to assignment 1-5? (yes or no)

- strong acids are the toxic ones

Assignment 1-7. Do you agree with this statement based on your answer to assignment 1-5? (yes or no)

Assignment 1-8. For all the five cases (water, strong/weak acid, strong/weak base) – click on the lamp sign. See how well the solutions conduct electricity. What trends do you see?

Acids and Bases. Imagine we can somehow measure molarity of hydronium (H_3O^+) and hydroxide (OH^-) ions in each of the 13 solutions from the Table below. For comparison purposes, all the solutions (except for pure water in beaker 1) are 0.10 mol/L.

All the measurements are done at room temperature.

Beaker	Solution	$[H_3O^+]$, M	$[OH^-]$, M	Acidic/Basic/Neutral	$[H_3O^+]\times[OH^-]$
1	H_2O	0.00000010 (1.0×10^{-7})	0.00000010 (1.0×10^{-7})	Acidic/Basic/Neutral	
2	0.10 M HCl	0.10 (1.0×10^{-1})	0.00000000000010 (1.0×10^{-13})	Acidic/Basic/Neutral	
3	0.10 M HF	0.0081 (8.1×10^{-3})	0.0000000000012 (1.2×10^{-12})	Acidic/Basic/Neutral	
4	0.10 M HNO_3	0.10 (1.0×10^{-1})	0.00000000000010 (1.0×10^{-13})	Acidic/Basic/Neutral	
5	0.10 M HNO_2	0.0071 (7.1×10^{-3})	0.0000000000014 (1.4×10^{-12})	Acidic/Basic/Neutral	
6	0.10 M $HClO_4$	0.10 (1.0×10^{-1})	0.00000000000010 (1.0×10^{-13})	Acidic/Basic/Neutral	
7	0.10 M H_2SO_3	0.036 (3.6×10^{-2})	0.00000000000028 (2.8×10^{-13})	Acidic/Basic/Neutral	
8	0.10 M H_2SO_4	0.11 (1.1×10^{-1})	0.000000000000091 (9.1×10^{-14})	Acidic/Basic/Neutral	
9	0.10 M H_3PO_4	0.027 (2.7×10^{-2})	0.00000000000037 (3.7×10^{-13})	Acidic/Basic/Neutral	
10	0.10 M $NaOH$	0.00000000000010 (1.0×10^{-13})	0.10 (1.0×10^{-1})	Acidic/Basic/Neutral	
11	0.10 M KOH	0.00000000000010 (1.0×10^{-13})	0.10 (1.0×10^{-1})	Acidic/Basic/Neutral	
12	0.10 M $Ca(OH)_2$	0.000000000000050 (5.0×10^{-14})	0.20 (2.0×10^{-1})	Acidic/Basic/Neutral	
13	0.10 M NH_3	0.0000000000075 (7.5×10^{-12})	0.0013 (1.3×10^{-3})	Acidic/Basic/Neutral	

Table 1.

Curious fact. Note that molarity is an intensive property – so it doesn't matter whether you have 1 drop, 1 L, or a million gallons of 0.10 M HCl (beaker 2), hydronium ion molarity [H_3O^+] in it will be 0.1 M.

Assignment 2-1. In each of the beakers 1-13, see what is in excess (H_3O^+ or OH^-) – assign the solutions accordingly, as acidic, neutral, or basic (mark in the Table 1).

Assignment 2-2. State (even if obvious) - what is your basis for assigning solutions as acidic, neutral, or basic?

We assigned solutions as acidic when:

We assigned solutions as neutral when:

We assigned solutions as basic when:

Assignment 2-3. Calculate [H_3O^+]×[OH^-] for each of the 12 beakers (divide the work among the members of your group, use a calculator, mark in the Table 1). Does your finding surprise you?

Assignment 2-4. Based on your finding, fill the missing information for the following 3 beakers in Table 2:

Beaker	Solution	[H_3O^+], M	[OH^-], M	Acidic/Basic/Neutral	[H_3O^+]×[OH^-]
14	0.10 M HBr	0.10 (1.0×10^{-1})		Acidic/Basic/Neutral	
15	0.10 M HI		0.00000000000010 (1.0×10^{-13})	Acidic/Basic/Neutral	
16	0.10 M LiOH		0.10 (1.0×10^{-1})	Acidic/Basic/Neutral	

Table 2.

Recap.

Assignment 2-5. Make guidelines for future students:

how can they find [H_3O^+] (if given [OH^-]), at room temperature?

how can they find [OH^-] (if given [H_3O^+]), at room temperature?

At elevated temperatures, concentrations of ions in water are slightly different from beaker 1's values, proton transfer happens to a greater extent.

Beaker	Solution	[H_3O^+], M	[OH^-], M	Acidic/Basic/Neutral	[H_3O^+]×[OH^-]
17 (at 60 °C)	H_2O	0.0000010 (1.0×10^{-6})	0.0000010 (1.0×10^{-6})		

Table 3.

Assignment 2-6. Does raising temperature change the neutrality of water?

Fixing a Misconception

Assignment 2-7. A student makes the following statement on an exam: "acidic solutions contain hydronium ions while basic solutions contain hydroxide ions." Is the student's statement correct, based on Tables 1 and 2? Explain.

Strong and Weak Acids and Bases.

Assignment 3-1. Based on your definition of strong and weak acids (assignment 1-5), which acids (from beakers 1-16) are strong? You should get six of them. In fact, these are the only six strong acids worth knowing (without getting into advanced chemistry courses). All the rest of the acids can safely be considered weak.

Six strong acids are:

Curious fact. Many acids have more than one proton in their structure, for example, diprotic acids H_2A and triprotic acids H_3A. Most acids of this kind are reluctant to give their first proton to water, even more reluctant to give their second and third proton to water (in other words, they are weak). But there is one acid (exceptional) that is strong in the first proton and weak in the second, see if you found it in your list of the six strong acids.

Assignment 3-2. Do you agree with this statement – that H_3PO_4 (all acids are equal concentrations) provide more $[H_3O^+]$ than diprotic H_2SO_3 and H_2SO_4 and those – more than monoprotic HCl or HF (see Table 1)? Explain.

Let’s switch to bases for a moment.

Assignment 3-3. In beaker 12, why is [OH^-] double of the initial concentration of the compound? Write a dissociation equation.

Assignment 3-4. Take a look at beaker 13. Try to write an equation of how NH_3 reacts with water. Your equation should explain why there’s an excess of [OH^-] relative to [H_3O^+] in NH_3 solution.

Introducing pH.

Now, try to see how inconvenient it would be if we spoke of $[H_3O^+]$ as it is: 0.01, 0.000001, 0.000001. Too many zeroes and too easy to make mistakes. Logarithm comes to rescue.

Assignment 4-1.

SIMULATION pHET/introduction/water (click on graph)

Calculate negative (to keep the final answers positive) log of $[H_3O^+]$ in water. This number is a lot more pleasant to work with than molarity of $[H_3O^+]$, it got common in the literature and is referred to as pH.

Beaker	Solution	$[H_3O^+]$, M	pH (predicted)
18	H_2O		
19	Strong acid HA		
20	Weak acid HA		

Table 4

Do the same (fill the predicted pH, Table 4) for

SIMULATION pHET/introduction/strong acid

SIMULATION pHET/introduction/weak acid

Curious note. Historically, pH was designed for aqueous solutions. This means that, properly speaking, there's no such thing as pH of a substance in alcohol, pH of a cloud of protons, pH of molten NaOH, etc.

Assignment 4-2.

Note that for bases, you still need $[H_3O^+]$ to calculate pH, however, their reactions with water include OH^-, not $[H_3O^+]$. Recall how to convert $[OH^-]$ to $[H_3O^+]$ (room temperature), and then calculate pH (predicted) of:

SIMULATION pHET/introduction/strong base

SIMULATION pHET/introduction/weak base

Beaker	Solution	$[H_3O^+]$, M	pH (predicted)
21	Strong base MOH		
22	Weak base B		

Table 5

pH Meters are useful devices to quickly and accurately measure pH of solutions. Use the pH meter function in each of the following to confirm predicted pH values of your solutions.

SIMULATION pHET/introduction/water

SIMULATION pHET/introduction/strong acid

SIMULATION pHET/introduction/weak acid

SIMULATION pHET/introduction/strong base

SIMULATION pHET/introduction/weak base

Were your measurements consistent with your predictions?

Assignment 4-3. Calculate pH values for the solutions below:
All the measurements are done at room temperature.

Beaker	Solution	$[H_3O^+]$, M	pH (2 decimal places)	Acidic/Basic/Neutral (copy from Table 1)
1	H_2O	0.00000010 (1.0×10^{-7})		Acidic/Basic/Neutral
2	0.10 M HCl	0.10 (1.0×10^{-1})		Acidic/Basic/Neutral
3	0.10 M HF	0.0081 (8.1×10^{-3})		Acidic/Basic/Neutral
4	0.10 M HNO_3	0.10 (1.0×10^{-1})		Acidic/Basic/Neutral
5	0.10 M HNO_2	0.0071 (7.1×10^{-3})		Acidic/Basic/Neutral
6	0.10 M $HClO_4$	0.10 (1.0×10^{-1})		Acidic/Basic/Neutral
7	0.10 M H_2SO_3	0.036 (3.6×10^{-2})		Acidic/Basic/Neutral
8	0.10 M H_2SO_4	0.11 (1.1×10^{-1})		Acidic/Basic/Neutral
9	0.10 M H_3PO_4	0.027 (2.7×10^{-2})		Acidic/Basic/Neutral
10	0.10 M NaOH	0.00000000000010 (1.0×10^{-13})		Acidic/Basic/Neutral
11	0.10 M KOH	0.00000000000010 (1.0×10^{-13})		Acidic/Basic/Neutral
12	0.10 M $Ca(OH)_2$	0.000000000000050 (5.0×10^{-14})		Acidic/Basic/Neutral
13	0.10 M NH_3	0.0000000000075 (7.5×10^{-12})		Acidic/Basic/Neutral

Table 6

Assignment 4-4. Based on Table 6, how does pH (at room temperature) for acidic substances compare to pH of water? How does pH of basic substances compare to pH of water?

Assignment 4-5. Is pH of equal concentration of strong acid and weak acid the same (beaker 2 and 3)? If it is different then in what way?

Assignment 4-6.

SIMULATION pHET/introduction/water (click on graph)
SIMULATION pHET/introduction/strong acid
SIMULATION pHET/introduction/weak acid
SIMULATION pHET/introduction/strong base
SIMULATION pHET/introduction/weak base

A quick way to have a rough estimate of pH of solutions is to use chemical dyes called indicators. Those dyes change color based on pH, the most common being litmus (isolated from certain moths). Click on the litmus tool and measure pH in the following:

Beaker	Solution	Litmus color and pH estimate
18	H_2O	
19	Strong acid HA	
20	Weak acid HA	
21	Strong base MOH	
22	Weak base B	

Which advantages and disadvantages do you foresee for the use of litmus indicators over pH meters.

Dependence of pH on Concentration.

All the measurements in this and following rubrics are done at room temperature.

Assignment 5-1.

SIMULATION pHET/mysolution/strong acid, click on graph

Use the simulation to find [H_3O^+] concentration in the acid solutions below (Table 7). Predict pH based on [H_3O^+]. Confirm with the pH meter that your pH calculation is accurate.

Beaker	Solution	[H_3O^+], M	pH
23	0.01 M strong acid (HA)		
24	0.02 M strong acid (HA)		
25	0.1 M strong acid (HA)		
26	1.0 M strong acid (HA)		

Table 7

Assignment 5-2. Which solution has a higher pH value: 0.01 M HA or 0.02 M HA? Without referring to the table, explain to future students why.

SIMULATION pHET/mysolution/strong base, click on graph

Use the simulation to find [OH^-] concentration in the base solutions before. Convert [OH^-] to pH (will require several steps). Confirm with the pH meter that your pH calculation is accurate.

Beaker	Solution	[OH^-], M	pH
23	0.01 M strong base (MOH)		
24	0.02 M strong base (MOH)		
25	0.1 M strong base (MOH)		
26	1.0 M strong base (MOH)		

Table 8

Fixing Misconceptions *(based on Tables 7-8)*

Students commonly write:

- pH of 0 is either undefined or it means there's no H_3O^+ in that solution.

Assignment 5-3. Do you agree with this statement?

- A solution of 0.02 M HCl is a stronger acid than a 0.01 M HCl solution.

Assignment 5-4. Do you agree with this statement based on your definition of strong/weak acids from assignments of level 3?

- pH varies from 1 to 14.

Assignment 5-5. Do you agree with this statement? Explain. According to the findings discovered in Tables 7 and 8, what would be pH of a 2.0 M strong acid HA and 2.0 M strong base MOH?

Recap.

It seems that knowing $[H_3O^+]$, you can easily calculate pH (see assignments level 2).

Assignment 5-6. Can you do the reverse – that is, calculate $[H_3O^+]$ given the pH? Explain how using example of pH = 3.

SIMULATION pHET/mysolution/weak acid, click on "molecules", select 1 M, the weakest possible. Check pH.

Assignment 5-7. As you move the toggle and increase the strength of the acid, what happens with the pH of the solution? Why does it change that way?

SIMULATION pHET/mysolution/strong acid, click on "graph", select 0.001 M. Check pH.

Assignment 5-8. As you move the toggle and increase the concentration of the acid, what happens with the pH of the solution? Why does it change that way?

SIMULATION pHET/mysolution/strong acid, click on “graph”, select 0.01 M. Check pH (pH = 2.00).
Assignment 5-9. To lower pH to 1 (make twice as small), do you expect to make the acid twice as concentrated (0.02 M)? Make you prediction first.

Then, move the “concentration” toggle to the right, to make pH change to 1. Look what concentration of acid it requires. Does your observation agree with the prediction?

pH of Aqueous Solutions of Salts

Look at how salt solutions affect [H_3O^+] (and, therefore, pH).

All the measurements are done at room temperature.

Beaker	Solution	[H_3O^+], M	pH
27	0.010 M NaCl	0.00000010 (1.0×10^{-7})	
28	0.010 M NaF	0.000000026 (2.6×10^{-8})	
29	0.010 M NH_4I	0.0000023 (2.3×10^{-6})	
30	0.010 M KBr	0.00000010 (1.0×10^{-7})	
31	0.010 M $ZnCl_2$	0.00000014 (1.4×10^{-7})	

Table 9

Assignment 6-1. Find the pH of all the salt solutions in Table 7.

In order to understand why salts affect pH, think of salts as MX (cation – M, anion - X) and of water as HOH. There's an equilibrium of salts in water which can be written as MX + HOH = MOH + HX. Products of this reaction have a direct effect on pH of the solution:

- *if HX is a strong acid, it fully releases all the H^+'s but if it is a weak acid it holds most of the H^+'s to itself.*
- *if MOH is an insoluble (like $Al(OH)_3$), it holds OH^-'s to itself, but if it is soluble (like NaOH or KOH), it fully releases all the OH^-'s.*

The tricky one here is NH_4OH – it's much better represented as NH_3 and H_2O rather than NH_4^+ and OH^- and, as such, does not release much of OH^- into solution.

- *Acidic/neutral/basic solution – this depends (as always) on what the balance is between H_3O^+ and OH^-.*

Assignment 6-2. Taking this into account, predict acidity/basicity/neutrality of: $CaCl_2$, KI, Li_2CO_3, $AlCl_3$, NH_4Cl.

Salt	Acidic/Basic/Neutral
$CaCl_2$	Acidic/Basic/Neutral
KI	Acidic/Basic/Neutral
Li_2CO_3	Acidic/Basic/Neutral
$AlCl_3$	Acidic/Basic/Neutral
NH_4Cl	Acidic/Basic/Neutral

Recap

SIMULATION Feel free to use SIMULATION to answer the questions below (if needed).

Assignment 6-3. Using words or pictures (or both), describe all species (molecules, ions) that are present in:

- a) Concentrated HCl solution vs dilute HCl solution
- b) HF solution
- c) $Ca(OH)_2$ solution
- d) NaCl solution vs NaF solution