AN INDICATORS PROBLEM

The following problem is a variation of an acid-base indicators experiment. This has been modified to be run in microscale, and to minimize safety hazards.

This problem was used in an academic competition where teams of students worked to solve the problem and then presented their results to a team of evaluators.

Before developing a list of factors for the evaluators to consider, the author presents a short tutorial on acids, bases, and pH. This is meant to give the evaluators the background the author worked from in developing the problem and the solution.

The background information and the factors that the evaluators looked for were first outlined by this author. That material was sent to outside evaluators, in the field, to criticize and modify. The comments and modifications were reviewed, corrections were made, and the modified material was again sent out for review and further modification. It should be noted, that the process of evaluating active assessment-type questions is a process that takes time and the input of several people. The goal is to try to develop a more objective evaluation that identifies the knowledge of the students working on the problem. The final answer is only a small part of this type of problem solving.

Most practical exams, administered in a small department setting, are evaluated in a somewhat subjective manner and the same criteria are not uniformly applied to all the students or teams working on the problem. This is not necessarily a result of favoritism toward certain students, although it may play a role, but rather a result of limited time for evaluation, different evaluators, or just a cursory scan of results where the evaluator concentrated mainly on the answer.

One may consider the extensive list of items to consider to be overkill for the problem, but it is important to develop a fair evaluation process. Another consideration is that all points are **positive points**, that is, students or teams get points added for each correct part of the solution to the problem. The author believes this produces more of a positive feedback to the student/team.

INDICATORS

Materials

0.10 M hydrochloric acid solution, HCl
0.10 M sodium hydroxide solution, NaOH
Distilled water
2 Indicator solutions labeled as "A" and "B"
Well plate, 48 wells
Droppers
Toothpick stirrers
Aluminum foil drip pan
Goggles
Rubber gloves

Task

Determine the color change(s) of each indicator.

Determine the pH range of the color change(s) for each indicator.

Define pH.

Explain how an indicator works.

Explain your method of solving this problem.

INDICATORS - Solution to the Problem

Note: The acid and base used in this procedure are very dilute and pose no safety or disposal problems

To determine the color change(s) of each indicator:

Students add a drop of indicator to some hydrochloric acid in one well of the well plate. Students add a drop of indicator to some sodium hydroxide in one well of the well plate.

NOTE: Some indicators may have an intermediate color between their two "end" colors. This procedure will **not** allow the students to determine any intermediate colors of the indicators.

To determine the pH range of the color change(s) for each indicator:

The students must use a method known as **successive dilutions**.
100 points for explaining this method

They start with the 0.1 M hydrochloric acid, which has a pH of 1. That is, they take one drop of the 0.1 M hydrochloric acid solution and add 9 drops of water to prepare a solution of pH 2. They then take one drop of pH 2 solution and dilute it with nine drops of water to prepare a solution of pH 3. Dilutions continue to a pH of 6.

The same procedure is used to dilute the 0.1 M sodium hydroxide solution which as a pH of 14. Successive dilute solutions will have pH values of 13, 12, 11, etc. Dilutions continue to a pH of 8

A solution with a pH of 7 is obtained by mixing 1 drop of the hydrochloric acid with one drop of the sodium hydroxide solution (i.e., equal drops of the acid and the base)
NOTE: Although water has a pH of 7, indicator solutions may have been prepared using small amounts of acids or bases to produce "standard laboratory solutions" and may not result in a true pH 7 color in water.

To define pH:

Water ionizes to produce hydrogen or hydronium ions, H^+ or H_3O^+, and hydroxide ions, OH^-, as shown in the equation below:

$$\underset{\text{Water}}{H_2O} = \underset{\text{hydrogen Ion}}{H^+} + \underset{\text{hydroxide ion}}{OH^-}$$

OR

$$2\,\underset{\text{Water}}{H_2O} = \underset{\text{hydronium Ion}}{H_3O^+} + \underset{\text{hydroxide ion}}{OH^-}$$

The concentration of water is 55.6 M (moles/liter) and the concentration of hydronium or hydroxide ions is 1x 10^{-7} M. This means that approximately one out of every billion molecules of water is ionized.

An acid is defined as a substance that produces hydronium (or hydrogen) ions in water solution and a base is defined as a substance that produces hydroxide ions in water solution.

To express the concentration of hydronium ions in acid solutions, we use a term called pH, sometimes referred to as the *power of hydrogen*, although the exact origin of the term pH is not clearly known. pH is defined as the negative logarithm of the hydrogen ion concentration:

$$pH = -\log [H^+]$$

The pH scale has a range from 1 to 14. A pH value between 1 and 7 represents an acid and a pH value between 7 and 14 represents a base. A pH value of 7 means the substance is neutral.

pH is a logarithmic scale. That means each pH unit represents a change in the H^+ concentration by a factor of 10. For example, an acid solution with a pH of 5 has 10 times more H^+ than an acid solution with a pH of 6. As pH values get lower, from 7 to 1, that means the acid, in comparison to other acids, is stronger, or it is producing more H^+. As pH values increase from 7 to 14, that means the base, in comparison to other bases, is stronger, or it is producing more OH^- (and less H^+). In water solution, pH values less than 1 or greater than 14 are not defined since we are beyond the capacity of the water to produce additional H^+ or OH^-.

To explain how an indicator works:

An indicator is a substance that changes color as the pH of a solution changes.

Most indicators are organic molecules that are weak acids and are colored in solution, or become colored either in contact with excess H^+ ions in solution, or as a result of losing H^+ ions in solution. Some indicators will have only two color changes while others go through an intermediate color between their “end” colors.

Depending on the pH of the color changes, and indicator can differentiate between an acid or a base, different degrees of acidity, or different degrees of basisity. For example, phenolphthalein, one of the most common indicators used, is colorless in acid solution and turns pink at a pH of 8 or higher, thus, it indicates the difference between and acid and a base. Another indicator, thymol blue, changes from red to yellow over a pH range from about 1 to 3, thus it indicates different degrees of acidity. Indicators are often used to indicate the end point in a titration (or measured reaction) between an acid and a base. The selection of the indicator depends on the pH of the final product of the acid-base titration, since the final compounds can have pH’s other than 7.

One can write a general equation for an indicator in solution:

$$\underset{\text{An indicator}}{\text{H-Iind}_{(aq)}} + \underset{\text{water}}{H_2O} = \underset{\text{hydronium ion}}{H_3O^+_{(aq)}} + \underset{\text{the indicator anion}}{Ind^-_{(aq)}}$$

The acid form of the indicator - color 1 The "base" form of the indicator – color 2

Generally, the equation can be summarized as the indicator, which is a weak acid, and has a specific color (called color 1 in the equation), can ionize to lose a hydrogen ion in water solution, resulting in an indicator anion which has a different color (called color 2 in the equation). In the presence of a larger concentration of hydrogen ions, the indicator will exhibit its acid color. In the presence of a small concentration of hydrogen ions (or a higher concentration of hydroxide ions), the indicator will exhibit its base color.

Explain your method of solving this problem.

The students should explain their solution of the problem in a systematic method utilizing the information listed above.

OPTIONAL:

Which indicator would be best for a titration of: (acid and base)?

Some Common Indicators that may be used for this Problem:

Identity	Color change	pH range
A. thymol blue	Red to yellow Yellow to blue	1.2 –2.8 8.0–9.2
B. phenol red	Yellow to red	6.4 – 8.2
C. bromphenol blue	Yellow to blue	3.0 – 4.6
D. alizarin yellow	Yellow to red	10.0 – 12.1
E. congo red	Blue to red	3.0 – 5.0

INDICATORS - Score sheet

500 points total

To determine the color change(s) of each indicator:

60 points total

20 points If students say they added indicator to some hydrochloric acid and to some sodium hydroxide.

20 points For the correct colors of the first indicator (see table, below)

20 points For the correct colors of the second indicator (see table, below)

Identity	Color change	pH range
A. thymol blue	Red to yellow Yellow to blue	1.2 –2.8 8.0–9.2
B. phenol red	Yellow to red	6.4 – 8.2
C. bromphenol blue	Yellow to blue	3.0 – 4.6
D. alizarin yellow	Yellow to red	10.0 – 12.1
E. congo red	Blue to red	3.0 – 5.0

NOTES: Some indicators may have an intermediate color between their two “end” colors. This part of the procedure will **not** allow the students to determine any intermediate colors of the indicators.
Thymol blue has two color changes. Students may only observe the red and blue colors in this part of the procedure. The students must determine the pH range for the color change to observe the intermediate yellow color.

To determine the pH range of the color change(s) for each indicator:

150 points total

10 points If the students use the term **successive dilutions**.

60 points If the students explain the method of successive dilutions.

They start with the 0.1 M hydrochloric acid, which has a pH of 1. They take one drop of the 0.1 M hydrochloric acid solution and add 9 drops of water to prepare a solution of pH 2. They then take one drop of pH 2 solution and dilute it with nine drops of water to prepare a solution of pH 3. Dilutions continue to pH of 6.

The same procedure is used to dilute the 0.1 M sodium hydroxide solution which as a pH of 14. Successive dilute solutions will have pH values of 13, 12, 11, etc. Dilutions continue to a pH of 8

10 points	If the students say that 0.1 M hydrochloric acid has a pH of 1
10 points	If the students say that 0.1 M sodium hydroxide has a pH of 14
10 points	If the students say the acid dilution continues to a pH of 6
10 points	If the students say the base dilution continues to a pH of 8
40 points	If the students say a solution with a pH of 7 is obtained by mixing 1 drop of the hydrochloric acid with one drop of the sodium hydroxide solution (i.e., equal drops of the acid and the base)
No points	If the students say water has a pH of 7.

NOTE: Although water has a pH of 7, indicator solutions may have been prepared using small amounts of acids or bases to produce "standard laboratory solutions". Such small amounts of acid or base will change the pH of the pure water.

To define pH:

190 points total

20 points	If students say that water ionizes to produce hydrogen or hydronium ions, H^+ or H_3O^+, and hydroxide ions, OH^-
20 points	If students write the equation $H_2O = H^+ + OH^-$
	OR the equation $2 H_2O = H_3O^+ + OH^-$
10 points	If the students say the concentration of water is 55.5 M or 55.6 M (moles/liter) (Note: Judges may give credit if the students say 55 M (moles/liter)
10 points	If the students say the concentration of hydronium (or hydrogen) ions in water is $1x 10^{-7}$ M. (Note: Accept 10^{-7} M as a correct answer)
10 points	If the students say the concentration of hydroxide ions in water is $1x 10^{-7}$ M. (Note: Accept 10^{-7} M as a correct answer)
10 points	If the students define an acid as a substance that produces hydronium (or hydrogen) ions in water solution
10 points	If the students define a base as a substance that produces hydroxide ions in water solution.

10 points	If the students say pH is sometimes referred to as the *power of hydrogen*
20 points	If the students define pH as the negative logarithm of the hydrogen ion concentration or use the equation:

$$pH = -\log [H^+]$$

10 points	If the students say the pH scale has a range from 1 to 14.
10 points	If the students say a pH value between 1 and 7 represents an acid
10 points	If the students say a pH value between 7 and 14 represents a base.
10 points	If the students say a pH value of 7 means the substance is neutral.
10 points	If the students say pH is a logarithmic scale.
10 points	If the students say that each pH unit indicates a change of hydrogen ion or hydroxide ion concentration by a factor of 10.
10 points	If the students say in water solution, pH values less than 1 or greater than 14 are not defined since we are beyond the capacity of the water to produce additional H^+ or OH^-.

To explain how an indicator works:

100 points total

10 points	If students say an indicator is a substance that changes color as the pH of a solution changes.
10 points	If students say most indicators are organic molecules that are weak acids and are colored in solution or become colored either in contact with excess H^+ ions in solution, or as a result of losing H^+ ions in solution.
10 points	If students explain some indicators will have only two color changes while others go through an intermediate color between their “end” colors.
10 points	If students say an indicator can differentiate between an acid or a base
10 points	If students say some indicators can differentiate between different degrees of acidity, or different degrees of basisity.
10 points	If students say the selection of the indicator depends on the pH of the final product of the acid-base titration, since the final compounds can have pH’s other than 7.

20 points   If the students can write a general equation for an indicator in solution:

$$Hind_{(aq)} + H_2O = H_3O^+_{(aq)} + Ind^-_{(aq)}$$

An indicator	water	hydronium ion	the indicator anion
The acid form of the indicator - color 1		The “base” form of the indicator – color 2	

20 points   For explaining the equation, above