AP® CHEMISTRY
2016 SCORING GUIDELINES

Question 4

$$C_6H_5OH(aq) + H_2O(l) \rightleftarrows C_6H_5O^-(aq) + H_3O^+(aq) \qquad K_a = 1.12 \times 10^{-10}$$

Phenol is a weak acid that partially dissociates in water, according to the equation above.

(a) What is the pH of a 0.75 M $C_6H_5OH(aq)$ solution?

$K_a = \frac{[C_6H_5O^-][H_3O^+]}{[C_6H_5OH]}$ $1.12 \times 10^{-10} = \frac{x^2}{(0.75 - x)}$ Assume that $x << 0.75$. $x^2 = 8.4 \times 10^{-11}$ $x = \sqrt{8.4 \times 10^{-11}}$ $x = 9.2 \times 10^{-6}\ M$ $pH = -\log[H^+] = -\log(9.2 \times 10^{-6}) = 5.04$	1 point is earned for a correct setup and calculation of $[H^+]$. 1 point is earned for the correct setup and calculation of pH based on a correct setup for the $[H^+]$ calculation.

(b) For a certain reaction involving $C_6H_5OH(aq)$ to proceed at a significant rate, the phenol must be primarily in its deprotonated form, $C_6H_5O^-(aq)$. In order to ensure that the $C_6H_5OH(aq)$ is deprotonated, the reaction must be conducted in a buffered solution. On the number scale below, circle <u>each</u> pH for which more than 50 percent of the phenol molecules are in the deprotonated form ($C_6H_5O^-(aq)$). Justify your answer.

Numbers 10 through 14 should be circled. When pH > pK_a , the deprotonated form will predominate. pK_a = $-\log(1.12 \times 10^{-10})$ = 9.95, therefore at pH 10 and above, $[C_6H_5O^-] > [C_6H_5OH]$.	1 point is earned for circling 10–14. 1 point is earned for the justification.

1 2 3 4 5 6 7 8 9 10 11 12 13 14

$$C_6H_5OH(aq) + H_2O(l) \rightleftarrows C_6H_5O^-(aq) + H_3O^+(aq) \qquad K_a = 1.12 \times 10^{-10}$$

4. Phenol is a weak acid that partially dissociates in water according to the equation above.

   (a) What is the pH of a 0.75 *M* $C_6H_5OH(aq)$ solution?

   (b) For a certain reaction involving $C_6H_5OH(aq)$ to proceed at a significant rate, the phenol must be primarily in its deprotonated form, $C_6H_5O^-(aq)$. In order to ensure that the $C_6H_5OH(aq)$ is deprotonated, the reaction must be conducted in a buffered solution. On the number scale below, circle <u>each</u> pH for which more than 50 percent of the phenol molecules are in the deprotonated form ($C_6H_5O^-(aq)$). Justify your answer.

1 2 3 4 5 6 7 8 9 (10) (11) (12) (13) (14)

a) $C_6H_5OH + H_2O \rightleftarrows C_6H_5O^- + H_3O^+$

	C_6H_5OH	H_2O	$C_6H_5O^-$	H_3O^+
I	0.75	—	0	0
C	$-x$	—	$+x$	$+x$
E	$0.75-x$	—	x	x

$$1.12 \times 10^{-10} = \frac{x^2}{0.75 - x} \qquad x << 0.75 \text{ because } k \text{ is very small}$$

$$1.12 \times 10^{-10} = \frac{x^2}{0.75}$$

$$x^2 = 8.4 \times 10^{-11}$$

$$x = 9.2 \times 10^{-6} = [H^+]$$

$$pH = -\log(9.2 \times 10^{-6}) = \boxed{5.04}$$

b) $pH = pK_a + \log \frac{[A^-]}{[HA]}$ when $\frac{[A^-]}{[HA]} > 1$, $A^- > 50\%$

$pH = pK_a$ when $\frac{[A^-]}{[HA]} = 1$

$= -\log(1.12 \times 10^{-10}) = 9.951$

when $\frac{[A^-]}{[HA]} > 1$, $pH > pK_a$

$pH > 9.951$

$pH = \boxed{10, 11, 12, 13, 14}$

When $[C_6H_5O^-] = [C_6H_5OH]$, $pH = pK_a = 9.951$.

For any solution where $[C_6H_5O^-] > [C_6H_5OH]$.

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ADDITIONAL PAGE FOR ANSWERING QUESTION 4

pH > pKa. In basic solutions with pH > pKa, the equilibrium is shifted to the left enough so that $[C_6H_5O^-] > [C_6H_5OH]$.

4B

$C_6H_5OH(aq) + H_2O(l) \rightleftarrows C_6H_5O^-(aq) + H_3O^+(aq) \qquad K_a = 1.12 \times 10^{-10}$

4. Phenol is a weak acid that partially dissociates in water according to the equation above.

(a) What is the pH of a 0.75 M $C_6H_5OH(aq)$ solution?

(b) For a certain reaction involving $C_6H_5OH(aq)$ to proceed at a significant rate, the phenol must be primarily in its deprotonated form, $C_6H_5O^-(aq)$. In order to ensure that the $C_6H_5OH(aq)$ is deprotonated, the reaction must be conducted in a buffered solution. On the number scale below, circle each pH for which more than 50 percent of the phenol molecules are in the deprotonated form ($C_6H_5O^-(aq)$). Justify your answer.

1 2 3 4 5 6 7 8 9 10 11 12 13 14

a)

R	C_6H_5OH	+ H_2O	⇌ $C_6H_5O^-$	+ H_3O^+
I	0.75		0	0
C	−x		+x	+x
E	0.75		x	x

$\frac{x^2}{0.75} = 1.12 \times 10^{-10}$

$x = 9.16 \times 10^{-6}$

$-\log(9.16 \times 10^{-6}) = 5.04$

pH = 5.04

$-\log([H_3O^+]) = -\log\left(\frac{[A^-][H_3O^+]}{[HA]}\right) = -\log\left(\frac{[A^-]}{[HA]}\right)$

b) $pH = -\log pK_a - \log\left(\frac{[A^-]}{[HA]}\right)$

$pH = 9.95 - \log\left(\frac{[A^-]}{[HA]}\right)$

According to this formula, whenever A^- (the deprotonated acid, or $C_6H_5O^-$) is larger than the concentration of HA, the pH will be below the pKa, or 9.95. As such, all pH's 9 or below will have a higher concentration of $C_6H_5O^-$ than HC_6H_5O

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4C

$$C_6H_5OH(aq) + H_2O(l) \rightleftarrows C_6H_5O^-(aq) + H_3O^+(aq) \qquad K_a = 1.12 \times 10^{-10}$$

4. Phenol is a weak acid that partially dissociates in water according to the equation above.

   (a) What is the pH of a 0.75 *M* $C_6H_5OH(aq)$ solution?

   (b) For a certain reaction involving $C_6H_5OH(aq)$ to proceed at a significant rate, the phenol must be primarily in its deprotonated form, $C_6H_5O^-(aq)$. In order to ensure that the $C_6H_5OH(aq)$ is deprotonated, the reaction must be conducted in a buffered solution. On the number scale below, circle each pH for which more than 50 percent of the phenol molecules are in the deprotonated form ($C_6H_5O^-(aq)$). Justify your answer.

1 2 3 4 5 6 7 8 9 (10) (11) (12) (13) (14)

(a) ~~$pH = -\log[0.75\,M]$~~ ~~$pH = 0.125$~~ ~~$pH = pKa + \log\frac{[A^-]}{[HA]}$~~ ~~$pH = \log\frac{[A^-]}{[HA]}$~~ $pH = 0$

$pH = pKa + \log\frac{[A^-]}{[HA]}$

$pH = 9.95 + 0$

$\boxed{pH = 9.95}$

(b) ~~deprotonated → more electrons~~ there are more products than reactants when the solution is more basic because $[A^-] > [HA]$ so $\log\frac{[A^-]}{[HA]} > 0$ which gets added to the pka making it more basic and greater than the original pH of 9.95.

AP® CHEMISTRY
2016 SCORING COMMENTARY

Question 4

Overview

Question 4 explored students' knowledge of weak acid equilibrium conditions in aqueous solution and conjugate acid/base relationships in a buffered solution. Students were given two scenarios involving solutions of phenol, C_6H_5OH (*aq*). In part (a) students were to calculate the pH of a 0.75 *M* solution of phenol given the K_a value for this weak acid. In part (b) students were asked to select pH values of a buffered solution that would ensure more than 50% of the phenol was in its deprotonated form, $C_6H_5O^-$(*aq*).

Sample: 4A
Score: 4

In part (a) 1 point was earned for setting up and correctly calculating $[H^+]$, and 1 point was earned for setting up and correctly calculating the pH. In part (b) 1 point was earned for circling numbers 10–14, and 1 point was earned for a justification that clearly describes buffers with a greater concentration of conjugate base than conjugate acid corresponding to a pH > pK_a.

Sample: 4B
Score: 3

In part (a) 1 point was earned for setting up and correctly calculating $[H^+]$, and 1 point was earned for setting up and correctly calculating the pH. In part (b) no point was earned for circling numbers 1–9; however, 1 point was earned for a justification consistent with the circled numbers. The student makes a sign error using the Henderson-Hasselbalch equation and matches the increasing concentration of conjugate base with a *decreasing* pH.

Sample: 4C
Score: 2

In part (a) neither of the two possible points were earned; the student calculates $[H^+]$ incorrectly and bases the calculation of pH on an incorrect application of the Henderson-Hasselbalch equation. In part (b) 1 point was earned for circling numbers 10–14, and 1 point was earned for a consistent justification that describes the increase of conjugate base concentration and increased base/acid ratio when pH > pK_a.