Part I: The pK_a of H_3O^+ and H_2O

1) What is the pK_a of H_3O^+?

$H_3O^+ + H_2O \Longleftrightarrow H_3O^+ + H_2O$

$$K_c = \frac{[H_3O^+][H_2O]}{[H_3O^+][H_2O]}$$

Multiplying both sides by $[H_2O]$ will give:

$$K_c [H_2O] = \frac{[H_3O^+][H_2O]}{[H_3O^+]}$$

Noting that $K_c [H_2O] = K_a$ and $[H_3O^+]$ cancels out, we arrive at:

$K_a = [H_2O] = 55.5$ M

$pK_a = -\log 55.5 = -\log 10^{1.74} = -1.74$

2) What is the pK_a of H_2O?

$H_2O + H_2O \Longleftrightarrow H_3O^+ + OH^-$

$$K_c = \frac{[H_3O^+][OH^-]}{[H_2O][H_2O]}$$

Multiplying both sides by $[H_2O]$ will give:

$$K_c [H_2O] = \frac{[H_3O^+][OH^-]}{[H_2O]}$$

Noting that $K_c [H_2O] = K_a$ and $[H_3O^+][OH^-] = K_w$, we arrive at:

$$K_a = \frac{K_w}{[H_2O]}$$

$K_a = (1.00 \times 10^{-14} \div 55.5) = (10^{-14} \div 10^{1.74}) = 10^{-15.74}$

$pK_a = -\log 10^{-15.74} = 15.74$

3) How do H_3O^+ and H_2O compare to each other in terms of acidic strength?

$\Delta pK_a = 15.74 - (-1.74) = 17.48$

Conclusion: H_3O^+ is a stronger acid than H_2O is by a factor of $10^{17.48}$.

4) How do other acids and bases compare to these two?

a) An acid (such as HCl) with a pK_a less than –1.74 is always fully ionized in H_2O. These acids all level out to the pK_a of H_3O^+.

b) Between the limits of $pK_a = -1.74$ (H_3O^+) and 15.74 (H_2O), the extent of ionization is directly proportional to the ΔpK_a.

Part II: The Extent of Acid Base Reactions

Nature always favors the weaker acid/base pair.

Remember the definition of pK_a: $-\log K_a$. The lower the pK_a, the stronger the acid.

Example #1

$HCl + H_2O$ <===> $H_3O^+ + Cl^-$

The pK_a of HCl = –7. The pK_a of H_3O^+ = –1.74.

$\Delta pKa = -7 - (-1.74) = -5.26$

This is an decrease in acid strength (from HCl to H_3O^+) by a factor of 1.82×10^5. This reaction is running downhill thermodynamically. Result: HCl is fully ionized in water solution. It is a strong acid.

Example #2

$HAc + H_2O$ <===> $H_3O^+ + Ac^-$

The pK_a of HAc = 4.75. The pK_a of H_3O^+ = –1.74.

$\Delta pK_a = 4.75 - (-1.74) = 6.49$

This is an increase in acid strength (from HAc to H_3O^+) by a factor 3.24×10^7. This reaction is running uphill thermodynamically. Result: acetic acid is partially ionized in water solution. It is a weak acid.

Example #3

$HCN + H_2O <===> H_3O^+ + CN^-$

The pK_a of HCN = 11. The pK_a of H_3O^+ = –1.74.

$\Delta pK_a = 11 - (-1.74) = 12.74$

This is an increase of acid strength (from HCN to H_3O^+) by a factor 5.50×10^{12}. This reaction is running uphill thermodynamically. Result: HCN is partially ionized in water solution. It is a weak acid.

Question: which is ionized more - 0.1 M HAc or 0.1 M HCN?
Answer: The HAc since it has less of an uphill battle to ionize than the HCN does.

Example #4

$Ac^- + H_2O <===> HAc + OH^-$

The pK_a of H_2O is 15.74. The pK_a of HAc is 4.75.

$\Delta pK_a = 15.74 - 4.75 = 10.99$

This is an increase of acid strength (from Ac^- to HAc) by a factor 9.77×10^{10}. This reaction is running uphill thermodynamically. Result: Ac^- partially hydrolyzes in water. It forms a slightly basic solution.

Example #5

$Cl^- + H_2O <===> HCl + OH^-$

The pK_a of H_2O is 15.74. The pK_a of HCl is –7.

$\Delta pK_a = 15.74 - (-7) = 22.74$

This is an increase of acid strength (from H_2O to HCl) by a factor 5.50×10^{22}. This reaction is running uphill thermodynamically. Result: Cl^- does not hydrolyze in water. It forms a neutral solution.

Example #6

$NaH + H_2O <===> H_2 + OH^-$

The pK_a of H_2O is 15.74. The pK_a of H_2 is 33.

$\Delta pK_a = 15.74 - 33 = -17.26$.

This is a decrease of acid strength (from H_2O to H_2) by a factor 1.82×10^{17}. This reaction is running downhill thermodynamically. Result: NaH reacts strongly with water, the H_2 escapes, leaving a basic solution.