1. (a) Look closely at what kind of atom rearrangement is taking place when each of the above reactions occurs in the forward direction. **What atom (or species) is moving from one reactant to the other?** Take whatever amount of time you need to see the pattern here. (b) Once you see the pattern, you should be able to fill in the blanks in the table with the proper chemical formulas.

   H⁺ is the species that is transferred

2. One definition of an acid is "a species that in a given reaction donates an H⁺ to another species". Which species are acting as acids in the reactions represented by the equations above?

   HCl, HNO₂, HClO, HCO₃⁻, H₂O, and HS⁻

3. One definition of a base is "a species that in a given reaction accepts an H⁺ from another species". (a) **Which species are acting as bases in the reactions represented by the equations above?**

   H₂O, in all of them (for the forward reactions)

   (b) Consider the reverse reactions in all the above equations. **Which species are acting as bases in each of those reverse reactions (represented by the reverse of the equations above)?**

   Cl⁻, NO₂⁻, ClO⁻, CO₃²⁻, OH⁻, S²⁻

4. Note that when an acid species donates an H⁺ to somebody else, the species that remains becomes a base! (e.g., If HClO₂ gives away an H⁺, it "becomes" ClO₂⁻, which can act as a base). And when a species that is a base accepts an H⁺, it becomes an acid species (e.g., If CN⁻ accepts an H⁺, it becomes the species HCN, which can act as an acid). **Species that "differ" by exactly ONE H⁺ are called "conjugates" (or conjugate acid-base pairs).** E.g., CN⁻ and HCN are conjugates, with CN⁻ being the base of the pair and HCN being the acid of the pair.

   **List the conjugates of the given acid or base species in the table:**

<table>
<thead>
<tr>
<th>(Conjugate) Acid</th>
<th>(Conjugate) Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>HNO₂</td>
<td>NO₂⁻</td>
</tr>
<tr>
<td>HSO₃⁻</td>
<td>SO₃²⁻</td>
</tr>
<tr>
<td>H₂O</td>
<td>OH⁻</td>
</tr>
<tr>
<td>OH⁻</td>
<td>O²⁻</td>
</tr>
<tr>
<td>H₃O⁺</td>
<td>H₂O</td>
</tr>
</tbody>
</table>

   All K values are at 298 K (25°C)
5. A "strong" acid is an acid for which nearly 100% of the dissolved formula units exist as separate ions. It can also be thought of as an acid that donates its H⁺ so much better than water that essentially all dissolved formula units of the acid end up without their H⁺ when equilibrium is reached.

Analyze the above statements carefully, along with the equilibrium equations and K values noted above, and answer the following: Which, if any of the acids in the above equations would be considered "strong" acids? Explain. (HINT: What does it mean if a value of K is large vs. small?)

The only strong acid in the list above is HCl. Its K value for donating its H⁺ ion to water is MUCH greater than 1, so "at equilibrium", the reaction is "product favored", which means that essentially all of the formula units of HCl have reacted (with H₂O molecules) to form Cl⁻ and H₃O⁺. There are essentially no HCl molecules (left) in solution at equilibrium.

6. A "weak" acid is (somewhat loosely) an acid for which much less than 100% (but not an insignificant %) of the dissolved formula units exist as separate ions. A more specific definition is "an acid that is not a strong acid, but which donates its H⁺ better than water does.

Analyze the above statement carefully, along with the equilibrium equations and K values noted above, and answer the following: Which, if any of the acids in the above equations would be considered "weak" acids?

HNO₂, HClO, and HCO₃⁻ would be considered to be weak acids. The K values for each one of them reacting with H₂O to yield their conjugate base and H₃O⁺ are greater than 10⁻¹⁴ (the effective value for water--please ask for some important but subtle info regarding this assertion), so they are "better" at donating H⁺ than water, but the K values are less than 1 (so they are not strong acids).

7. Acids that are poorer at donating their H⁺ than water is are (in my class) called "negligible" acids. They are capable of donating H⁺'s in principle, but in water, the amount of H⁺'s that are donated to water is considered negligible since other water molecules donate more H⁺'s than the "acid" does.

Which acid(s) in the above list would be considered "negligible" by this definition?

HS⁻ is considered a negligible acid (in water). Its K value is 100,000 times smaller than the K for water, and so essentially no significant amount of H₃O⁺ ions will form from this reaction compared to the amount of H₂O⁺ ions that will form in pure water from the reaction of water molecules with one another.

8. What do you think it would mean if "Acid HA₁ is stronger than Acid HA₂"? Does it mean that HA₁ is a strong acid?

HA₁ is a stronger acid than HA₂ if its Kₐ value is larger. It does NOT mean that HA₁ is a strong acid! It just means that it has a greater tendency to give away its H⁺. (Think of it this way: two people can both be physically weak, but one can be strongER than the other one!) The difference here is between ABSOLUTE "strength" (strong vs. weak vs negligible) and RELATIVE "strength" (strongER or weakER). Note that all weak acids, are by definition stronger than any negligible acid.

9. Which acid(s) above is/are stronger than HClO? What does that mean in a practical sense?

HCl and HNO₂ are stronger than HClO. They each have a greater tendency to give their H⁺ away than does HClO. We measure "strength" here by giving TO WATER to have a standard for comparison, but acids can donate their H⁺ (to different degrees, of course!) to any potential base.

10. What do you think it would mean if "Acid HA₁ is weaker than Acid HA₂"? Does it mean that HA₁ is a weak acid?

HA₁ is a weaker acid than HA₂ if its Kₐ value is smaller. It doesn't mean that it is a weak acid. All negligible acids are, by definition weaker than any weak acid, for example.
11. a) What is $K$ for the following equation:

$$\text{NO}_2^-(aq) + \text{H}_2\text{O}(l) \leftrightarrow \text{HNO}_2(aq) + \text{OH}^-(aq)$$

(Hint: Use Equations (2) and (5) above and try to get an equation that sums up to the above; then use the rules for relating $K$'s for equations (i.e., $K_{1+2} = K_1K_2$).)

$$\text{NO}_2^-(aq) + \text{H}_3\text{O}^+(aq) \leftrightarrow \text{HNO}_2(aq) + \text{H}_2\text{O}(l) \quad K = \frac{1}{K_a} = \frac{1}{4.5 \times 10^{-4}}$$

$$\text{H}_2\text{O}(l) + \text{H}_2\text{O}(l) \leftrightarrow \text{OH}^-(aq) + \text{H}_3\text{O}^+(aq) \quad K_w = 1.0 \times 10^{-14}$$

$$\text{NO}_2^-(aq) + \text{H}_2\text{O}(l) \leftrightarrow \text{HNO}_2(aq) + \text{OH}^-(aq) \quad K = \frac{K_{w}}{K_a} = \frac{1.0 \times 10^{-14}}{4.5 \times 10^{-4}} = 2.2 \times 10^{-11}$$

b) Write out all of the equations of the form "base + H$_2$O(l) $\leftrightarrow$ conjugate acid + OH$^-$ (aq)" for ALL of the bases on the right hand side of the equations at the front of this document (Basically do what you did in part (a) above for all of the equations at the beginning, except for (2) which was done in (a)).

c) Then figure out all of the $K$ values for the equations in (b) above, as you did in part (a).

<table>
<thead>
<tr>
<th></th>
<th>All K values are at 298 K (25°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1')</td>
<td>Cl$^-$ (aq) + H$_2$O(l) $\leftrightarrow$ HCl(aq) + OH$^-$ (aq)</td>
</tr>
<tr>
<td>(2')</td>
<td>NO$_2^-$ (aq) + H$_2$O(l) $\leftrightarrow$ HNO$_2$(aq) + OH$^-$ (aq)</td>
</tr>
<tr>
<td>(3')</td>
<td>ClO$^-$ (aq) + H$_2$O(l) $\leftrightarrow$ HClO(aq) + OH$^-$ (aq)</td>
</tr>
<tr>
<td>(4')</td>
<td>CO$_3^{2-}$ (aq) + H$_2$O(l) $\leftrightarrow$ HCO$_3^-$ (aq) + OH$^-$ (aq)</td>
</tr>
<tr>
<td>(5')</td>
<td>OH$^-$ (aq) + H$_2$O(l) $\leftrightarrow$ H$_2$O(l) + OH$^-$ (aq)</td>
</tr>
<tr>
<td>(6')</td>
<td>S$^{2-}$ (aq) + H$_2$O(l) $\leftrightarrow$ HS$^-$ (aq) + OH$^-$ (aq)</td>
</tr>
</tbody>
</table>

12. (a) Look back at questions 5-7 and see if you can come up with reasonable definitions for "strong base", "weak base", and "negligible base". (You can abbreviate here!)

**strong base**: a species for which every formula unit of the species ends up generating an OH$^-$ ion in aqueous solution*

This can occur one of TWO WAYS: either

a) the species' $K_b > 1$ \ OR \ b) the substance is any soluble hydroxide (strong electrolyte)

**weak base**: a species for which some (but not 100%) of the formula units end up generating OH$^-$ ions in solution*; it is better at taking H$^+$ from H$_2$O than H$_2$O, but it is not so good of an H$^+$ acceptor that it is "strong". Its $K_b$ is greater than 10$^{-14}$ but less than 1.
**Answers: Introduction to Acid-Base Concepts and Equilibria**

negligible base: a species whose \( K_b \) is less than \( 10^{-14} \); it's so poor at taking \( H^+ \) from water that at equilibrium, essentially no significant increase in \( OH^- \) is observed above the \([OH^-]\) in pure water

*Strictly speaking, one should include a phrase like "starting with a decent concentration" in all of these statements, since % ionization depends on initial concentration as well as \( K \) such that at extremely low concentration, % ionization approaches infinity.

(b) Based on your definitions in (a), which of the bases in the equations above are:

i) strong  
ii) weak  
iii) negligible

\[
\begin{align*}
S^{2-}, CO_3^{2-}, ClO^-, NO_2^- & \quad \text{strong} \\
Cl^- & \quad \text{weak} \\
\quad \text{negligible}
\end{align*}
\]

**OH\(^-\) doesn't easily fit into the definitions above. NaOH would be a strong base, but OH\(^-\) alone is impossible to add to a solution. Non-hydroxide containing compounds are bases only to the extent that they "produce" OH\(^-\) in aqueous solution by reacting with water. Since OH\(^-\) is "already" OH\(^-\), it really doesn't make much sense to write its "\( K_b \)" equation or value. I left it there for completeness, but the best you can say is its "\( K_b \)" value represents a "benchmark" value. (Non-hydroxide) bases are strong bases only if their \( K_b \) is greater than one; those that are weak have \( K_b \) less than one.**

13. If an acid is **strong**, is its conjugate base strong, weak, or negligible? Look closely at your answers to 5-7 and 12, and look for the "pattern". If an acid is **weak**, is its conjugate base strong, weak, or negligible? If a base is weak, is its conjugate acid strong, weak, or negligible? Do the answers make sense conceptually? Explain.

If an acid is _____________, its conjugate base is _____________

<p>| | |</p>
<table>
<thead>
<tr>
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<th></th>
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<tbody>
<tr>
<td><strong>strong</strong> (e.g., HCl; ( K_a \approx 10^7 ))</td>
<td><strong>negligible</strong> (e.g., Cl(^-); ( K_b \approx 10^{-21} ))</td>
</tr>
<tr>
<td><strong>weak</strong> (e.g., HNO(_2); ( K_a = 4.5 \times 10^{-4} ))</td>
<td><strong>weak</strong> (e.g., NO(_2^-); ( K_b = 2.2 \times 10^{-10} ))</td>
</tr>
<tr>
<td><strong>negligible</strong> (e.g., HS(^-); ( K_b = 1 \times 10^{-19} ))</td>
<td><strong>strong</strong> (e.g., S(^2-); ( K_b = 10^5 ))</td>
</tr>
</tbody>
</table>

**General Statement:** The stronger an acid, the weaker is its conjugate base.

**Conceptual "Rationalization":** The better a species is at giving away its proton (the greater its "tendency" to give it away), then the poorer will be the "tendency" of the conjugate base (what's left over after the \( H^+ \) has been given away!) to pull that proton back (from anybody).

-- So, once an acid gets "so" strong that it is actually a "strong acid", its conjugate will be "so" weak that is actually a negligible base. "Strong" and "weak" ARE NOT OPPOSITES--"strong" and "negligible" are the opposites where acids and bases are concerned!

(Note: All \( K \) values in these tables are at 25 °C.)

(Continues on next page)

If a base is _____________, its conjugate acid is _____________

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>strong</strong> (e.g., S(^2-); ( K_b = 10^5 ))</td>
<td><strong>negligible</strong> (e.g., HS(^-); ( K_a = 1 \times 10^{-19} ))</td>
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<td><strong>weak</strong> (e.g., NO(_2^-); ( K_b = 2.2 \times 10^{-10} ))</td>
<td><strong>weak</strong> (e.g., HNO(_2); ( K_a = 4.5 \times 10^{-4} ))</td>
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<tr>
<td><strong>negligible</strong> (e.g., Cl(^-); ( K_b \approx 10^{-21} ))</td>
<td><strong>strong</strong> (e.g., HCl; ( K_a \approx 10^7 ))</td>
</tr>
</tbody>
</table>

**General Statement:** The stronger a base, the weaker is its conjugate acid.

**Conceptual "Rationalization":** The better a species is at taking away somebody else's proton (the greater its "tendency" to take it away), then the poorer will be the "tendency" of the conjugate acid (what's formed after the \( H^+ \) has been taken from somebody!) to give that proton back (to anybody).

-- So, once a base gets "so" strong that it is actually a "strong base", its conjugate will be "so" weak that is actually a negligible acid. "Strong" and