**Bond Order and Bond Strength**

(Are All Bonds Created Equal?)

**Model 1: Single, Double, and Triple Bonds.**

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Lewis Structure</th>
<th>Bond</th>
<th>Bond Order</th>
<th>Bond Energy (kJ/mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>H – H</td>
<td>H–H</td>
<td>1</td>
<td>436</td>
</tr>
<tr>
<td>Cl₂</td>
<td>:Cl – Cl:</td>
<td>Cl–Cl</td>
<td>1</td>
<td>243</td>
</tr>
<tr>
<td>H₂O</td>
<td>:O–H</td>
<td>O–H</td>
<td>1</td>
<td>498</td>
</tr>
<tr>
<td>H₃CCH₃</td>
<td>H–C–C–H</td>
<td>C–C</td>
<td>1</td>
<td>376</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂CCH₂</td>
<td>H–C≡C–H</td>
<td>C–C</td>
<td>2</td>
<td>720</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C–H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>:O=C=O</td>
<td>C–O</td>
<td>2</td>
<td>804</td>
</tr>
<tr>
<td>H₂CO</td>
<td>H–C–H</td>
<td>C–O</td>
<td>2</td>
<td>782</td>
</tr>
<tr>
<td>N₂</td>
<td>:N≡N:</td>
<td>N–N</td>
<td>3</td>
<td>945</td>
</tr>
<tr>
<td>HCCCH</td>
<td>H–C≡C–H</td>
<td>C–C</td>
<td>3</td>
<td>962</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C–H</td>
<td>1</td>
<td>552</td>
</tr>
</tbody>
</table>

The bond energy is defined as the energy required to sever the bond that holds two adjacent atoms together in a molecule. This energy is usually expressed on a molar basis (as the energy to break one mole of specified bonds).
Critical Thinking Questions

1. Verify (using your checklist) that the Lewis structure for $\text{H}_2\text{CCH}_2$ given in Table 1 is correct.

   Correct

2. The title of Model 1 identifies three types of bonds. Give two examples of each type of bond from the molecules in Table 1.

   - Single: $\text{H} - \text{H}$
   - Double: $\text{H} = \text{C} = \text{H}$
   - Triple: $\text{N} = \text{N}$

3. What is the relationship between the bond order of a bond and the designation of single, double, and triple bonds?

   - 1st order = single bond
   - 2nd order = double bond
   - 3rd order = triple bond

4. What is the relationship between the bond order and the number of electrons shared by two adjacent atoms?

   - 1st order = 2 e-
   - 2nd order = 4 e-
   - 3rd order = 6 e-

5. Rank the three types of bonds of Model 1 in order of increasing strength.

   Single < double < triple
## Model 2: Bond Orders and Bond Energies for Selected Molecules.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Lewis Structure</th>
<th>Bond</th>
<th>Bond Order</th>
<th>Bond Energy (kJ/mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF</td>
<td>H–F</td>
<td>H–F</td>
<td>1</td>
<td>570</td>
</tr>
<tr>
<td>HCl</td>
<td>H–Cl</td>
<td>H–Cl</td>
<td>1</td>
<td>432</td>
</tr>
<tr>
<td>HBr</td>
<td>H–Br</td>
<td>H–Br</td>
<td>1</td>
<td>366</td>
</tr>
<tr>
<td>HI</td>
<td>H–I</td>
<td>H–I</td>
<td>1</td>
<td>298</td>
</tr>
<tr>
<td>Cl₂</td>
<td>Cl–Cl</td>
<td>Cl–Cl</td>
<td>1</td>
<td>243</td>
</tr>
<tr>
<td>Br₂</td>
<td>Br–Br</td>
<td>Br–Br</td>
<td>1</td>
<td>193</td>
</tr>
<tr>
<td>I₂</td>
<td>I–I</td>
<td>I–I</td>
<td>1</td>
<td>151</td>
</tr>
<tr>
<td>H₃CCH₃</td>
<td>H–C–C–H</td>
<td>C–C</td>
<td>1</td>
<td>376</td>
</tr>
<tr>
<td>H₂CCH₂</td>
<td>H–C≡C–H</td>
<td>C–C</td>
<td>2</td>
<td>720</td>
</tr>
<tr>
<td>CO₂</td>
<td>O=O</td>
<td>C=O</td>
<td>2</td>
<td>804</td>
</tr>
<tr>
<td>H₂CO</td>
<td>H–C–H</td>
<td>C–O</td>
<td>2</td>
<td>782</td>
</tr>
<tr>
<td>N₂</td>
<td>N≡N</td>
<td>N=N</td>
<td>3</td>
<td>945</td>
</tr>
<tr>
<td>HCCCH</td>
<td>H–C≡C–H</td>
<td>C–C</td>
<td>3</td>
<td>962</td>
</tr>
</tbody>
</table>
Critical Thinking Questions

6. Consider the series HF, HCl, HBr, HI.
   a) What is the bond order for each H–X bond?
      \[ \text{Single bond} \]
      \[ 1\text{st order} \]
   b) What trend is observed in bond energy?
      \[ HF > HCl > HBr > HI \]
   c) Considering the relative size of F, Cl, Br, and I, what trend would you predict in H–X bond length? Bond length is defined as the distance between the nuclei of two bonding atoms.
      \[ HF < HCl < HBr < HI \]
      Because size of halogen increases from F → Cl → Br → I.

7. Consider the series Cl₂, Br₂, I₂.
   a) What is the bond order for each X–X bond?
      \[ \text{Triple bond} \]
   b) What trend is observed in bond energy?
      \[ Cl₂ > Br₂ > I₂ \]
   c) Considering the relative size of Cl, Br, and I, what trend would you predict in X–X bond length?
      \[ Cl₂ < Br₂ < I₂ \]

8. Which of the following statements appears to be true from CTQs 6 and 7? Explain.
   a) The longer the bond, the stronger the bond.
   b) The shorter the bond, the stronger the bond.

   HF is the shortest and strongest bond in Cl₂ is the shortest and strongest bond in Cl₂
9. In Model 2,
   a) What is the range of bond energies for all single bonds?
      \[ 15 \text{ kJ/mol to } 570 \text{ kJ/mol} \]
   b) What is the range of bond energies for all double bonds?
      \[ 720 \text{ kJ/mol to } 804 \text{ kJ/mol} \]
   c) What is the range of bond energies for all triple bonds?
      \[ 945 \text{ kJ/mol to } 962 \text{ kJ/mol} \]

10. Based on your answers to CTQs 6-9 and the data in Model 2, explain how the following conclusion can be reached:

    The most important determinant of bond strength is bond order. If the bond orders are the same, the shorter the bond the stronger the bond.

**Exercises**

1. Which C–C bond is harder to break?

    \[
    \begin{align*}
    \text{Cl} & \quad \text{Cl} \\
    \text{C} & \quad \text{C} \\
    \text{Cl} & \quad \text{Cl} \\
    \end{align*}
    \] 
    or 
    \[
    \begin{align*}
    \text{Cl} & \quad \text{Cl} \\
    \text{C} & \quad \text{C} \\
    \text{Cl} & \quad \text{Cl} \\
    \end{align*}
    \]

2. Which C–C bond is harder to break?

    \[
    \begin{align*}
    \text{H} & \quad \text{C} \equiv \text{C} & \quad \text{H} \\
    \text{H} & \quad \text{H} \\
    \text{H} & \quad \text{C} = \text{C} & \quad \text{H} \\
    \end{align*}
    \] 
    or 
    \[
    \begin{align*}
    \text{H} & \quad \text{C} \equiv \text{C} & \quad \text{H} \\
    \text{H} & \quad \text{H} \\
    \text{H} & \quad \text{C} = \text{C} & \quad \text{H} \\
    \end{align*}
    \]

3. Which C–N bond is stronger?

    \[
    \begin{align*}
    \text{H} & \quad \text{C} \equiv \text{H} \\
    \text{H} & \quad \text{H} \\
    \text{N} & \quad \text{H} \\
    \text{H} & \quad \text{C} \equiv \text{N} & \quad \text{H} \\
    \end{align*}
    \] 
    or 
    \[
    \begin{align*}
    \text{H} & \quad \text{C} \equiv \text{H} \\
    \text{H} & \quad \text{H} \\
    \text{N} & \quad \text{H} \\
    \text{H} & \quad \text{C} \equiv \text{N} & \quad \text{H} \\
    \end{align*}
    \]

4. Using grammatically correct English sentences, describe the relationships between bond order, bond energy, and the number of electrons shared in a bond.

   Higher bond order means higher bond energy and more electrons are shared in the bond.
5. The skeletal structures (structures that indicate the arrangement of atoms in a molecule) for formaldehyde and methanol are shown below:

\[
\begin{align*}
\text{H} & \quad \text{H} \\
\backslash & \quad \backslash \\
\text{C} & \quad \text{H} \\
\text{O} & \quad \text{H} \\
\end{align*}
\]

Is the following statement true or false? (Explain your answer.)

It takes more energy to break the C–O bond in formaldehyde than to break the C–O bond in methanol. [Hint: draw the Lewis structure for each molecule.]

\text{True:} \quad \text{C}–\text{O} \text{ in formaldehyde is 2nd order while} \quad \text{C}–\text{O} \text{ in methanol is 3rd order.}

6. A rule of thumb states that about 300 kJ is required to break one mole of single bonds. Predict the bond energy of double bonds (in kJ/mole) based on this rule of thumb. Predict the bond energy of triple bonds (in kJ/mole) based on this rule of thumb. Compare your predictions to values in Table 1.

7. Consider molecules of the type

\[
\begin{align*}
\text{H} & \\
\backslash & \\
\text{H}–\text{C}–\text{X} & \\
\backslash & \\
\text{H} &
\end{align*}
\]

where X = F, Cl, Br, I.

a) Based on atomic radii, which do you expect to have the longest bond length, C–F, C–Cl, C–Br, C–I? Which do you expect to have the shortest bond length? Explain your reasoning.

\text{Longest:} \quad \text{C}–\text{I} \text{ shortest:} \quad \text{C}–\text{F} \text{ is because F is smaller than I.}

b) Which do you expect to have the strongest bond, C–F, C–Cl, C–Br, C–I? Which do you expect to have the weakest bond? Explain your reasoning.

\text{C}–\text{F strongest} \quad \text{C}–\text{I weakest}

8. For each of the following, which has the stronger bond between the two bold atoms? Give a brief explanation. (Hint: write the Lewis Structure for each molecule.)

a) H₃C and H₃SiH

\text{Smaller C vs. Si.}

b) N₂ and O₂

\text{Larger bond order N vs O.}

c) H₂PH and HOH

\text{Smaller O vs P.}

d) HSH and HOH

\text{Smaller O vs S.}

e) HSH and HSeH

\text{Smaller S vs Se.}

f) H₂PH and H₂NH

\text{Smaller N vs P.}

g) F₂ and O₂

\text{Larger bond order O vs F.}
9. Rank N₂, P₂, As₂, in order from weakest to strongest bond.

\[ \text{Weakest} \quad \text{As}_2 \quad \text{P}_2 \quad \text{N}_2 \quad \text{Strongest} \]

10. Indicate whether each of the following statements is true or false and explain your reasoning.

a) The bonds in NH₃ are shorter than the bonds in NF₃. \[ \text{True: } F \text{ is smaller than } N \]

b) The bonds in CCl₄ are stronger than the bonds in CBr₄. \[ \text{True: } F \text{ is smaller than } Br \]

c) The carbon–nitrogen bond in H₃CNH₂ is easier to break than the carbon–nitrogen bond in HCN. \[ \text{True} \]


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**Problem**

1. Which molecule or ion has the strongest bond between the two atoms: OH⁻; HS⁻; HF; HCl; HI? Explain.