1. In order to form a set of sp\(^2\) hybrid orbitals, how many pure atomic orbitals of each type must be mixed?
   (a) one s and two p   (b) two s and two p
   (c) two s and one p   (d) one s and three p

2. In order to form a set of sp\(^3\) hybrid orbitals, how many pure atomic orbitals of each type must be mixed?
   (a) one s and two p   (b) two s and two p
   (c) two s and one p   (d) one s and three p

3. Which of the following elements is most likely to display dsp\(^3\) hybridization?
   (a) oxygen       (b) nitrogen
   (c) phosphorus      (d) carbon

4. Which of the following elements is most likely to display d\(^2\)sp\(^3\) hybridization?
   (a) fluorine   (b) sulfur
   (c) nitrogen        (d) carbon

5. What is the maximum number of hybrid orbitals that can be formed by oxygen?
   (a) three        (b) four
   (c) five            (d) six

6. What is the maximum number of hybrid orbitals that can be formed by boron?
   (a) three        (b) four
   (c) five            (d) six

7. Atomic orbitals will combine most effectively to form molecular orbitals when the atomic orbitals have similar
   (a) number of electrons     (b) energies
   (c) hybridization               (d) bond order

8. What is the effect of electrons in antibonding orbitals upon the bond order?
   (a) Each antibonding electron increases the bond order by one.
   (b) Each antibonding electron increases the bond order by one-half.
   (c) Each antibonding electron decreases the bond order by one.
   (d) Each antibonding electron decreases the bond order by one-half.

9. What is the effect of electrons in bonding orbitals upon the bond order?
   (a) Each bonding electron increases the bond order by one.
   (b) Each bonding electron increases the bond order by one-half
   (c) Each bonding electron decreases the bond order by one.
   (d) Each bonding electron decreases the bond order by one-half.

NOTE: For spring 2001 do not answer underlined questions having to do with molecular orbital theory.
10. What is the maximum number of hybrid orbitals that a phosphorus atom may form?
   (a) three  (b) four
   (c) six    (d) eight

11. What type of hybrid orbital set is used by the nitrogen atom in the molecule NH₃?
    (a) sp   (b) sp²
    (c) sp³  (d) d²sp³

12. What type of hybrid orbital set is used by the sulfur atom in the compound H₂S?
    (a) sp   (b) sp²
    (c) sp³  (d) d²sp³

13. What type of hybrid orbital set is used by the beryllium atom in the compound BeF₂?
    (a) sp   (b) sp²
    (c) sp³  (d) d²sp³

14. What type of hybrid orbital set is used by the boron atom in the compound BF₃?
    (a) sp   (b) sp²
    (c) sp³  (d) d²sp³

15. What type of hybrid orbital set is used by the xenon atom in the compound XeF₄?
    (a) sp   (b) sp²
    (c) sp³  (d) d²sp³

16. What type of hybrid orbital set is used by the sulfur atom in the compound SF₆?
    (a) sp   (b) sp²
    (c) sp³  (d) d²sp³

17. What type of hybrid orbital set is used by the boron atom in the BCl₄⁻ ion?
    (a) sp   (b) sp²
    (c) sp³  (d) d²sp³

18. What type of hybrid orbital set is used by the nitrogen atom in the NH₄⁺ ion?
    (a) sp   (b) sp²
    (c) sp³  (d) d²sp³

19. What type of hybrid orbital set is used by the aluminum atom in the AlF₆³⁻ ion?
    (a) sp   (b) sp²
    (c) sp³  (d) d²sp³
20. Which of the following statements regarding pi bonding is incorrect?
(a) Pi (\(\pi\)) bonds do not occur unless the bonded atoms are already being joined by a sigma (\(\sigma\)) bond.
(b) In order for a pi (\(\pi\)) bond to form, there must be an unhybridized p atomic orbital on the atom where the hybridization will occur.
(c) The number of pi (\(\pi\)) bonds formed will equal the number of atomic orbitals on the hybridized atom.
(d) All three of the above statements are correct.

21. What hybrid orbital set is used by the underlined carbon atom in the allene molecule?
\[
\begin{align*}
&\text{H} & \text{H} \\
&\text{H} & \equiv & \equiv & \text{C} & \equiv & \equiv & \text{C} & \equiv & \text{H}
\end{align*}
\]
(a) sp \\
(b) \(\text{sp}^2\) \\
(c) \(\text{sp}^3\) \\
(d) \(\text{d}^2\text{sp}^3\)

22. What hybrid orbital set is used by the underlined carbon atom in the following molecule?
\[
\begin{align*}
&\text{H} & \text{H} \\
&\text{H} & \equiv & \equiv & \text{C} & \equiv & \equiv & \text{C} & \equiv & \text{H}
\end{align*}
\]
(a) sp \\
(b) \(\text{sp}^2\) \\
(c) \(\text{sp}^3\) \\
(d) \(\text{d}^2\text{sp}^3\)

23. What hybrid orbital set is used by the oxygen atom in the following molecule?
\[
\begin{align*}
&\text{H} & \equiv & \equiv & \text{C} & \equiv & \equiv & \text{O} & \equiv & \text{C} & \equiv & \text{H} \\
&\text{H} & \equiv & \equiv & \text{H}
\end{align*}
\]
(a) sp \\
(b) \(\text{sp}^2\) \\
(c) \(\text{sp}^3\) \\
(d) \(\text{d}^2\text{sp}^3\)
24. Methylbenzoate, called “oil of Niobe,” is used in perfumes.

(i) What hybrid orbital set is used by carbon atom 1 in benzoic acid?
(a) sp  
(b) $sp^2$
(c) $sp^3$
(d) $d^2sp^3$

(ii) What hybrid orbital set is used by carbon atom 2 in the above molecule?
(a) sp$^3$
(b) $sp^2$
(c) $sp^3$
(d) $d^2sp^3$

(iii) What hybrid orbital set is used by carbon atom 3 in the above molecule?
(a) sp
(b) $sp^2$
(c) $sp^3$
(d) $d^2sp^3$

(iv) What hybrid orbital set is used by oxygen atom 1 in the above molecule?
(a) sp
(b) $sp^2$
(c) $sp^3$
(d) $d^2sp^3$

25. What hybrid orbital set is used by the indicated carbon atom in the following molecule?

(a) sp
(b) $sp^2$
(c) $sp^3$
(d) $d^2sp^3$

26. What hybrid orbital set is used by the sulfur atom in the following molecule?

(a) sp
(b) $sp^2$
(c) $sp^3$
(d) $d^2sp^3$

27. What hybrid orbital set is used by the nitrogen atom in the following molecule?

(a) sp
(b) $sp^2$
(c) $sp^3$
(d) $d^2sp^3
28. What type of orbital set is used by the nitrogen atom in nitric acid?

\[ \begin{array}{c}
\text{O} \equiv \text{N} \equiv \text{O} \\
\text{O} \equiv \text{H}
\end{array} \]

(a) sp (b) sp\(^2\) (c) sp\(^3\) (d) d\(^2\)sp\(^3\)

**MOLECULAR ORBITALS**

The molecular orbital diagram below can be used in answering questions 29-43.

Energy

\[ \sigma_{2p}^* \]

\[ \pi_{2p}^* \]

\[ \sigma_{2p} \]

\[ \pi_{2p} \]

\[ \sigma_{2s}^* \]

\[ \sigma_{2s} \]

\[ \sigma_{1s}^* \]

\[ \sigma_{1s} \]

29. A molecular orbital that decreases the electron probability between the nuclei is said to be ________

(a) antibonding (b) nonbonding (c) bonding (d) hybridized

30. Which of the following statements regarding molecule orbital theory is **not** correct?

(a) The number of molecular orbitals formed is equal to the number of atomic orbitals contributed by the atoms involved.

(b) Electrons are assigned to orbitals of successively higher energy.

(c) The Pauli Principle is obeyed.

(d) A bonding molecular orbital is higher in energy than the parent atomic orbital from which it was formed.
31. In a diatomic molecule, when two atomic orbitals of the same type combine to form molecular orbitals, which of the following statements best describes the energy of the resulting pair of molecular orbitals?
   (a) Both molecular orbitals will be higher in energy than the component atomic orbitals.
   (b) Both molecular orbitals will be lower in energy than the component atomic orbitals.
   (c) One molecular orbital will be higher in energy and one will be lower in energy than the component atomic orbitals.
   (d) Both molecular orbitals will be identical in energy to the component atomic orbitals.

32. According to the molecular orbital theory, which of the following correctly lists these hydrogen species in terms of increasing bond order?
   (a) $\text{He}_2 < \text{He}_2^+ < \text{He}_2^{2+}$
   (b) $\text{He}_2^+ < \text{He}_2 < \text{He}_2^{2+}$
   (c) $\text{He}_2^{2+} < \text{He}_2^+ < \text{He}_2$
   (d) $\text{He}_2^{2+} < \text{He}_2 < \text{He}_2^+$

33. According to molecular orbital theory, which of the following species is unlikely to exist?
   (a) $\text{H}_2$
   (b) $\text{H}_2^+$
   (c) $\text{He}_2^+$
   (d) $\text{He}_2$

34. According to the molecular orbital theory, which of the following correctly lists the following oxygen species in terms of increasing bond order?
   (a) $\text{O}_2^+ < \text{O}_2^- < \text{O}_2$
   (b) $\text{O}_2^+ < \text{O}_2 < \text{O}_2^-$
   (c) $\text{O}_2^- < \text{O}_2^+ < \text{O}_2$
   (d) $\text{O}_2^- < \text{O}_2 < \text{O}_2^+$

35. According to the molecular orbital theory, which of the following correctly lists these carbon species in terms of increasing bond length?
   (a) $\text{C}_2^+ < \text{C}_2^- < \text{C}_2$
   (b) $\text{C}_2^+ < \text{C}_2 < \text{C}_2^-$
   (c) $\text{C}_2^- < \text{C}_2^+ < \text{C}_2$
   (d) $\text{C}_2^- < \text{C}_2 < \text{C}_2^+$

36. According to molecular orbital theory, which of the following species is unlikely to exist?
   (a) $\text{Li}_2^-$
   (b) $\text{Li}_2$
   (c) $\text{Be}_2^-$
   (d) $\text{Be}_2^+$

37. According to the molecular orbital theory, which of the following molecules has a bond order of two?
   (a) $\text{Be}_2$
   (b) $\text{F}_2$
   (c) $\text{C}_2$
   (d) $\text{B}_2$

38. According to the molecular orbital theory, which of the following molecules has a bond order of three?
   (a) $\text{N}_2$
   (b) $\text{F}_2$
   (c) $\text{O}_2$
   (d) $\text{Be}_2$

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39. According to the molecular orbital theory, which of the following molecules is paramagnetic?
   (a) $\text{Be}_2$  
   (b) $\text{F}_2$  
   (c) $\text{C}_2$  
   (d) $\text{B}_2$

40. Consider the simple molecule NO, nitrogen oxide.
   (i) What is the highest energy molecular orbital to which an electron or electrons have been assigned?

   (ii) How many net sigma ($\sigma$) bonds are there? ______

   (iii) How many net pi ($\pi$) bonds? ______

   (iv) What is the $\text{N}—\text{O}$ bond order? ______

   (v) Is the molecular diamagnetic or paramagnetic? __________________

   (vi) If the molecule is oxidized to the nitrosonium ion, NO$^+$, the N—O bond is (longer)(shorter) _______, and it is (stronger)(weaker) ______ than in NO.

41. Assuming that the molecular orbital energy level diagram for a homonuclear diatomic molecule applies to a heteronuclear molecule such as NO, which of the following correctly lists these nitrogen oxide species in terms of increasing bond order?
   (a) NO$^+$ < NO$^-$ < NO  
   (b) NO$^+$ < NO < NO$^-$  
   (c) NO$^-$ < NO$^+$ < NO  
   (d) NO$^-$ < NO < NO$^+$

42. According to the molecular orbital energy level diagram given in the text, which of the following molecules has the highest bond order? (Assume the molecular orbital energy level diagram for a homonuclear diatomic molecule applies to heteronuclear diatomic molecules.)
   (a) OF  
   (b) CO  
   (c) NO  
   (d) BN

43. According to the molecular orbital energy level diagram given in the text, which of the following ions has the highest bond order? (Assume the molecular orbital energy level diagram for a homonuclear diatomic molecule applies to heteronuclear diatomic molecules.)
   (a) Ar$^+_2$  
   (b) OF$^-$  
   (c) CN$^-$  
   (d) NF$^2$-

44. The elements called ______ are characterized by the fact that the valence band is only partly filled.
   (a) metals  
   (b) semiconductors  
   (c) nonmetals  
   (d) allotropes

45. What name is given to the highest filled energy level in a metal at absolute zero?
   (a) conduction band  
   (b) antibonding orbital  
   (c) band gap  
   (d) Fermi level

46. What do we call a material in which the band gap between the conduction band and the valence band is very large?
   (a) intrinsic semiconductor  
   (b) conductor  
   (c) insulator  
   (d) extrinsic semiconductor

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47. What do we call a material such as silicon, in which the band gap between the conduction band and the valence band is small?
   (a) intrinsic semiconductor (b) conductor
   (c) insulator (d) extrinsic semiconductor

48. Cysteine is one of the natural amino acids.

   \[ \text{CH}_2 \text{C}_\text{C} \text{O—H} \]
   \[ \text{H} \]
   \[ \text{H} \]
   \[ \text{N} \text{O} \]
   \[ \text{H} \text{H} \]
   \[ \text{carbon 1} \]
   \[ \text{angle 1} \]
   \[ \text{angle 2} \]
   \[ \text{angle 3} \]
   \[ \text{carbon 2} \]

   (i) The molecule has _______ sigma (\(\sigma\)) bonds and _______ pi (\(\pi\)) bonds.
   (ii) Estimate the values of the indicated angles:
   Angle 1 = _____ Angle 2 = _____ Angle 3 = _____
   (iii) Consider the S—C bond. The orbital hybridization scheme used by the S atom is _______ and that used by the C atom (carbon 1) is _______.
   (iv) What is the hybrid orbital set used by carbon 2? ___________

49. The compound \(\text{C}_5\text{H}_8\text{O}_2\) exists in two forms in equilibrium with one another. (Lone pairs are not shown.)

   \[ \text{H}_3\text{C} \equiv \text{C} \text{C} \text{CH}_3 \]
   \[ \text{H} \]
   \[ \text{angle 1} \]
   \[ \text{Form A} \]

   \[ \text{H}_3\text{C} \text{C} \text{C} \text{CH}_3 \]
   \[ \text{H} \text{H} \]
   \[ \text{O O} \]
   \[ \text{Form B} \]

   (i) What change occurs in the hybrid orbital set used by C atom 3?
   (a) changes from \(\text{sp}\) to \(\text{sp}^2\) (b) changes from \(\text{sp}\) to \(\text{sp}^3\)
   (c) changes from \(\text{sp}^2\) to \(\text{sp}^3\) (d) changes from \(\text{sp}^3\) to \(\text{sp}^2\)
   (ii) What change occurs in angle 1?
   (a) changes from 120’ to 109’ (b) changes from 180’ to 109’
   (c) changes from 109’ to 120 (d) changes from 120’ to 90
50. The molecule below is used as a pesticide. (The molecule lies in the yz plane. Lone pairs are not shown.)

(i) The hybrid orbital set used by carbon atom 1 is _____, by carbon 2 is ____, and by the N atom is ______.
(ii) The C—N= C bond angle is ______ and the N=C=S bond angle is ______.
(iii) The C—N=C=S framework is planar. Assume these atoms lie in the xy plane. Now consider the orbitals (2s, 2p_x, 2p_y, and 2p_z) on carbon atom 2. The orbitals on this atom that are involved in hybrid orbital formation are ______, and the orbitals on C atom 2 that are used in π bond formation with the neighboring N and S atoms are ____________.
(iv) Which is the shorter carbon-nitrogen bond in the molecule, H_3C—N or C=N?
(v) Which is the weaker carbon-nitrogen bond in the molecule, H_3C—N or C=N?
### ANSWERS — CHAPTER 10

1. a  
2. d  
3. c  
4. b  
5. b  
6. b  
7. b  
8. d  
9. b  
10. c  
11. c  
12. c  
13. a  
14. b  
15. d  
16. d  
17. c  
18. c  
19. d  
20. c  
21. a  
22. b  
23. c  
24. i = b, ii = b, iii = c, iv = c  
25. c  
26. c  
27. b  
28. b  
29. a  
30. d  
31. c  
32. a  
33. d  
34. d  
35. b  
36. c  
37. c  
38. a  
39. d  
40. \text{i = } \pi^*; \; \text{ii = 1; } 50. \text{i = } \text{sp}^3, \text{sp}, \text{sp}^2; \text{ii = 120}', 180'; \text{iii = 1 1/2; iv = 2 1/2; } \text{iii = } s, p_x, p_y, p_z; \text{iv = C=N; } v = H_3C—N \text{; } v = \text{paramagnetic; } \text{vi = shorter, stronger}

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