

3.4 COVALENT AND COORDINATE COVALENT BONDING

Learning outcomes

Candidates should be able to:

1 define covalent bonding

(a) describe covalent bonding in molecules including:

- hydrogen, H_2 • oxygen, O_2 • nitrogen, N_2 • chlorine, Cl_2
- hydrogen chloride, HCl • carbon dioxide, CO_2 • ammonia, NH_3
- methane, CH_4 • ethane, C_2H_6 • ethene, C_2H_4

understand that elements in period 3 can expand their octet including in the compounds sulfur dioxide, SO_2 , phosphorus pentachloride, PCl_5 , and sulfur hexafluoride, SF_6

(c) describe coordinate (dative covalent) bonding, including in the reaction between ammonia and hydrogen chloride gases to form the ammonium ion, NH_4^+ , and in the Al_2Cl_6 molecule

2 (a) describe covalent bonds in terms of orbital overlap giving σ and π bonds:

- σ bonds are formed by direct overlap of orbitals between the bonding atoms
- π bonds are formed by the sideways overlap of adjacent p orbitals above and below the σ bond

(b) describe how the σ and π bonds form in molecules including H_2 , C_2H_6 , C_2H_4 , HCN and N_2

(c) use the concept of hybridisation to describe sp , sp^2 and sp^3 orbitals

3 (a) define the terms:

- bond energy
- bond length

(b) use bond energy values and the concept of bond length to compare the reactivity of covalent molecules

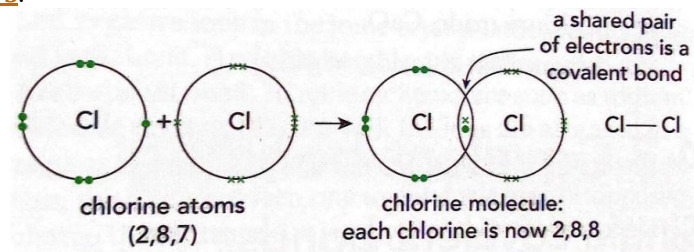
Covalent bonding

Covalent bonding is an electrostatic attraction between the **nuclei of two atoms** and **shared pair/s of electrons**.

When two non-metal atoms combine, they share one or more pairs of electrons. A shared pair of electrons is called a **single covalent bond**, or a **bond pair**.

A single covalent bond is represented by a single line between the atoms: for example, $Cl-Cl$.

When chlorine atoms combine not all the electrons are used in bonding. The pairs of outer-shell electrons not used in bonding are called **lone pairs**.



This interactive tutorial explains how covalent bonds are formed:

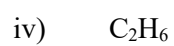
<https://contrib.pbslearningmedia.org/WGBH/arct15/SimBucket/Simulations/chemthink-covalentbonding/content/index.html>

double covalent bond: two shared pairs of electrons bonding two atoms together.

Define triple covalent bond.

Draw the dot and cross diagram to show the single covalent bonds in

i) HCl



Draw the dot and cross diagram to show the double covalent bonds in





Draw the dot and cross diagram to show the covalent bonds in



1. Hydrocarbon molecules contain covalent bonds.
Define a covalent bond.

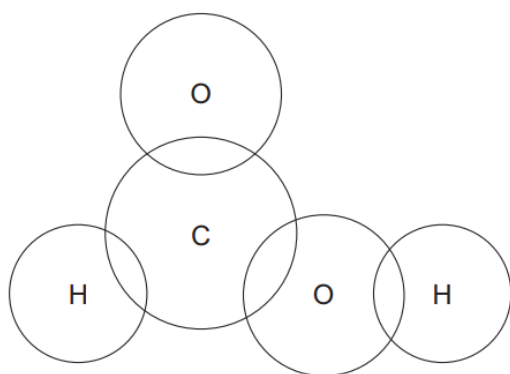
[1]

2. Species such as NH_4^+ , CO_3^{2-} and PO_4^{3-} are examples of molecular ions. Ionic and covalent bonds both involve an electrostatic attraction between different species. Identify the species that are electrostatically attracted to one another in:
- a covalent bond.

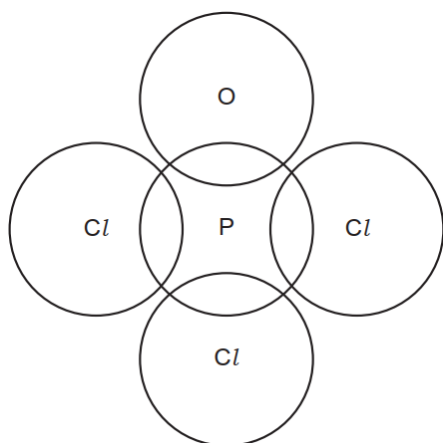
[1]

3. Complete the 'dot-and-cross' diagram, showing outer electrons only, to show the bonding in methanoic acid, HCO_2H .

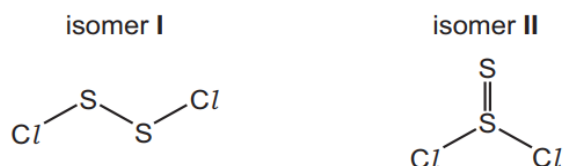
[2]



4. POCl_3 contains a double covalent bond between P and O. Complete the dot-and-cross diagram, in Fig. 1.1, to show the bonding in POCl_3 . Show outer shell electrons only.



5. The following figure shows the two structural isomers of S_2Cl_2 .

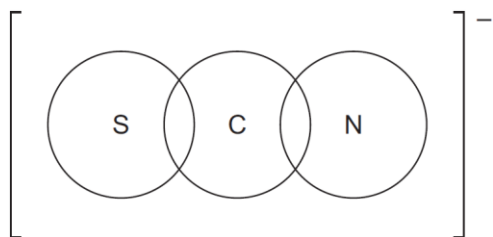


Draw a dot-and-cross diagram to show the bonding in isomer II. Show outer shell electrons only.

[2]

6. $\text{SCN}^-(\text{aq})$ is colourless.

Complete the dot-and-cross diagram in Fig. 3.1 to show the arrangement of outer electrons in an SCN^- ion.



[2]

7. Sulfides are compounds that contain sulfur but not oxygen.

Carbon disulfide, CS_2 , is a volatile liquid at room temperature and pressure.

Draw a 'dot-and-cross' diagram of the CS_2 molecule.

[2]

8. Draw a 'dot-and-cross' diagram of a PI_3 molecule.

[2]

9. Chlorine forms several oxides, including Cl_2O , ClO_2 and Cl_2O_6 .

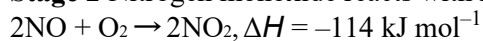
Draw a 'dot-and-cross' diagram of Cl_2O . Show outer-shell electrons only.

[1]

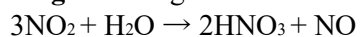
10. Nitric acid can be made in a 3-stage process.

Stage 1 Ammonia is oxidised by oxygen from the air, to form nitrogen monoxide and water. This reaction is carried out at 10–13 atmospheres pressure and 900°C in the presence of a platinum catalyst.

Stage 2 Nitrogen monoxide reacts with more oxygen to form nitrogen dioxide.



Stage 3 Nitrogen dioxide reacts with water to make nitric acid and nitrogen monoxide.



Draw a 'dot-and-cross' diagram to show the arrangement of outer electrons in a molecule of ammonia. [2]

1. Which molecule contains eight bonding electrons?

A CO_2

B C_2H_4

C C_3H_6

D NH_3

2. Which molecule contains six bonding electrons?

A NCI_3

B H_2S

C C_2H_4

D SF_6

3. In which species is there a lone pair of electrons?

A CH_4

B CH_3^+

C CH_3^-

D CH_3

4. Which molecule has an equal number of bonding electrons and lone-pair electrons?

A BH_3

B CO_2

C F_2O

D SO_2

5. Which molecules contain at least one unpaired electron?

1 NO 2 NO₂ 3 NH₃

A only 1 B 1 and 2 C all three D only 3

6. In which species does the underlined atom have an incomplete outer shell?

A BF₃ B CH₃- C F₂O D H₃O⁺

7. In which species does the underlined atom have an incomplete outer shell?

A Al₂Cl₆ B CH₃⁺ C Cl₂O D H₂ClC•

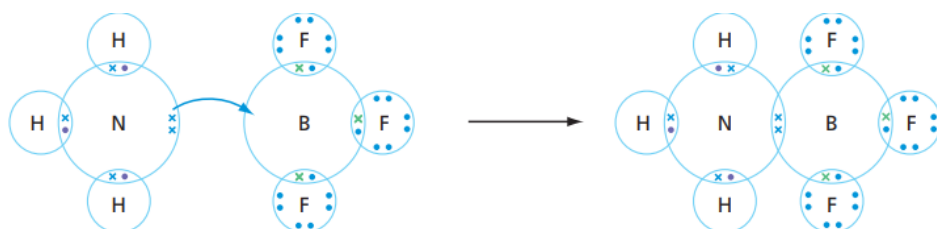
8. An ion contains 1 nitrogen atom and 2 hydrogen atoms. It has an H–N–H bond angle of approximately 105°. Which row is correct?

	number of lone pairs around N in ion	overall charge on ion
A	1	+1
B	2	+1
C	1	-1
D	2	-1

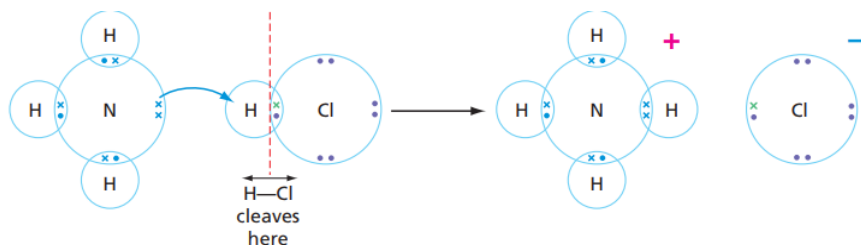
Coordinate covalent bonding

It is possible for just one of the atoms to provide both bonding electrons. This atom is called the **donor atom**, and the two electrons it provides come from a lone pair on that atom. The other atom in the bond is called the **acceptor atom**. It must contain an empty orbital in its valence shell. This kind of bonding is called **dative bonding** or **co-ordinate bonding**. The apparent covalency of each atom can increase as a result of dative bonding.

For example, when gaseous ammonia and gaseous boron trifluoride react together, a white solid is formed, with the formula NH₃BF₃. The nitrogen atom in ammonia has a lone pair and the boron atom in boron trifluoride has an empty 2p orbital.



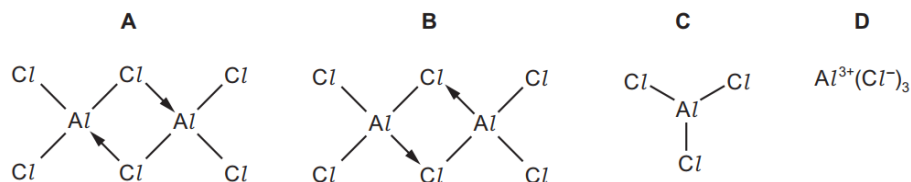
The dative bond, once formed, is no different from any other covalent bond.



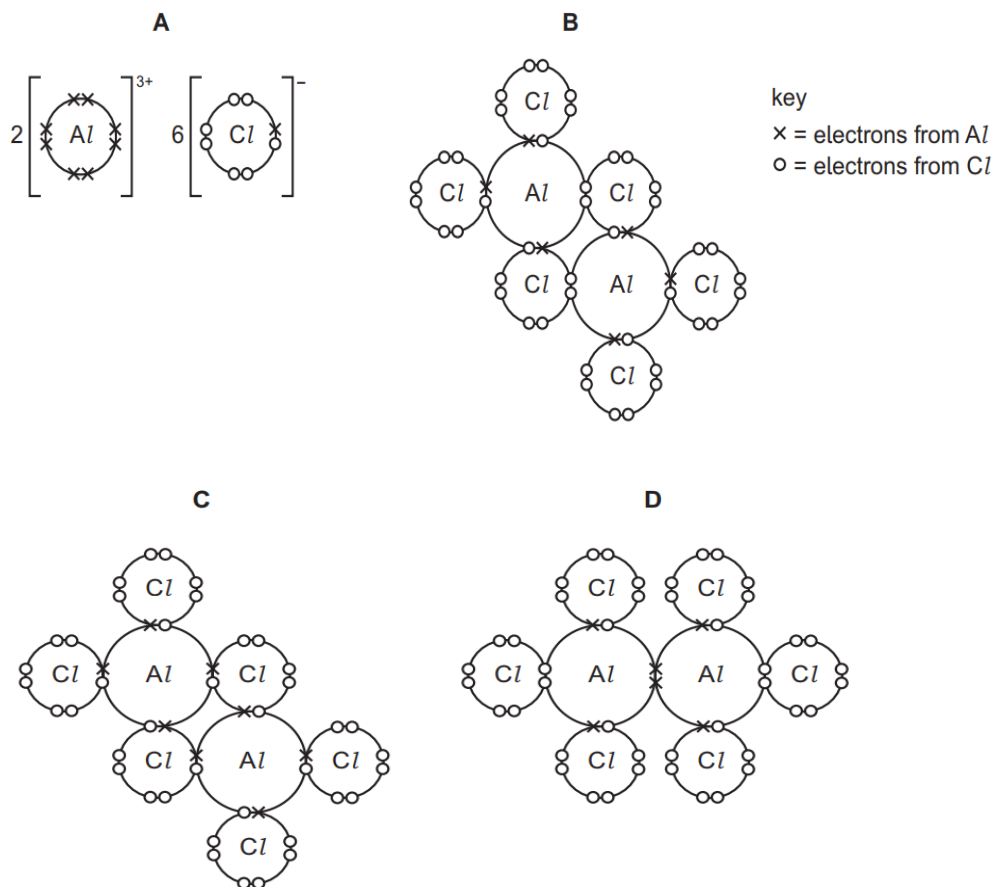
9. Phosphorus forms a compound with hydrogen called phosphine, PH_3 . This compound can react with a hydrogen ion, H^+ . Which type of interaction occurs between PH_3 and H^+ ?

A dative covalent bond
B dipole–dipole forces
C hydrogen bond
D ionic bond

10. Solid aluminium chloride sublimes at 178°C . Which structure best represents the species in the vapour at this temperature?



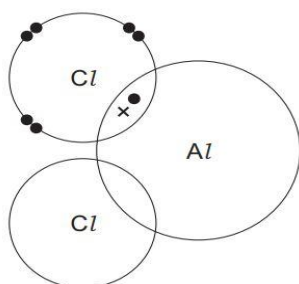
11. Which dot-and-cross diagram is correct for Al_2Cl_6 ?



11. In the gas phase, $\text{AlCl}_3(\text{g})$ exists at equilibrium with $\text{Al}_2\text{Cl}_6(\text{g})$ as shown.



Complete the dot-and-cross diagram to show the bonding in Al_2Cl_6 .



[2]

12. The reducing agent LiAlH_4 can be synthesised by reacting aluminium chloride with lithium hydride, LiH . At 200°C , aluminium chloride exists as $\text{Al}_2\text{Cl}_6(\text{g})$. Draw the structure of $\text{Al}_2\text{Cl}_6(\text{g})$, showing fully any coordinate (dative covalent) bonds in the molecule.

[2]

12. When solid aluminium chloride is heated, Al_2Cl_6 is formed.

Which bonding is present in Al_2Cl_6 ?

- A** covalent and coordinate (dative covalent)
- B** covalent only
- C** ionic and coordinate (dative covalent)
- D** ionic only

13. At 200°C aluminium chloride is a gas with $M_r = 267$.

What is the number of covalent bonds, dative covalent bonds and lone pairs of electrons in one molecule of aluminium chloride at 200°C ?

	Covalent bonds	Dative covalent bonds	lone pairs
A	6	2	0
B	6	2	16
C	6	2	18
D	3	0	9

14. Which elements form a chloride in which both covalent bonding and coordinate (dative covalent) bonding are present?

- 1** Al **2** Si **3** Mg

13. Gallium is a metal in Group 13 of the Periodic Table.

Gallium and its compounds show similar properties to aluminium and its compounds.

When gallium trichloride is cooled a solid, Ga_2Cl_6 , forms.

Suggest the name of the attraction formed between two gallium trichloride molecules to form Ga_2Cl_6 .

[1]

14. Carbon monoxide, CO, is a gas at room temperature and pressure. The atoms in a molecule of CO are held together by a triple covalent bond. One of these bonds is a coordinate (dative covalent) bond.

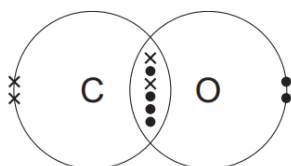
(i) Explain what is meant by a coordinate bond. [1]

(ii) Draw a 'dot-and-cross' diagram to show the arrangement of outer electrons in CO.

Show the electrons belonging to the C atom as ✕.

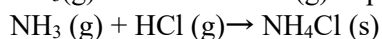
Show the electrons belonging to the O atom as ●. [2]

15. Carbon monoxide gas, CO(g), and nitrogen gas, N₂(g), are both diatomic molecules. The diagram shows the arrangement of outer electrons in a molecule of CO(g).



State **one** similarity and **one** difference in the way the atoms in a carbon monoxide molecule are bonded together compared to the atoms in a nitrogen molecule. [2]

16. NH₃(g) reacts with HCl (g) to produce NH₄Cl (s), as shown.



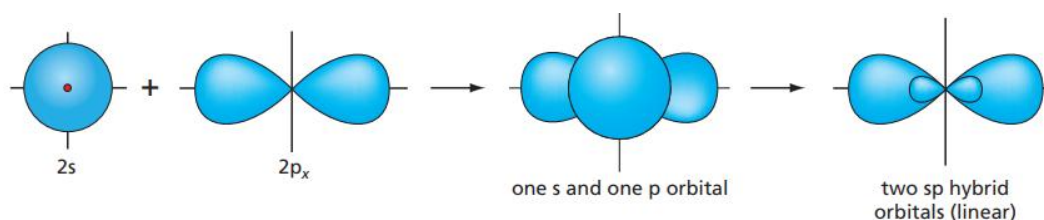
Draw a diagram to show the ionic, covalent and coordinate bonding present in a formula unit of NH₄Cl. [2]

Hybridisation

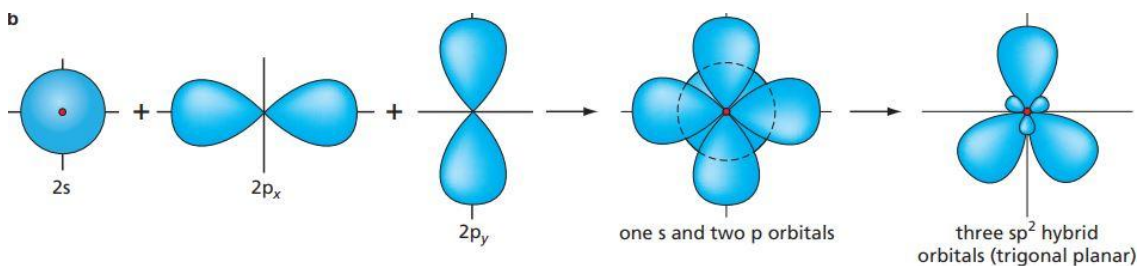
Covalent bonds are formed when atomic orbitals overlap.

The mixing of atomic orbitals is called hybridisation.

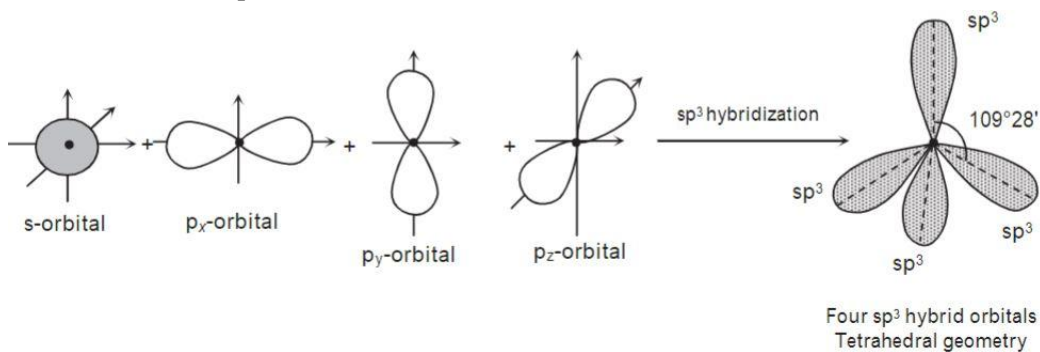
When one s orbital and one p orbital are hybridised, the hybrids are called **sp orbitals**.



When one s orbital and two p orbitals are hybridised, the hybrids are called **sp² hybrids**.



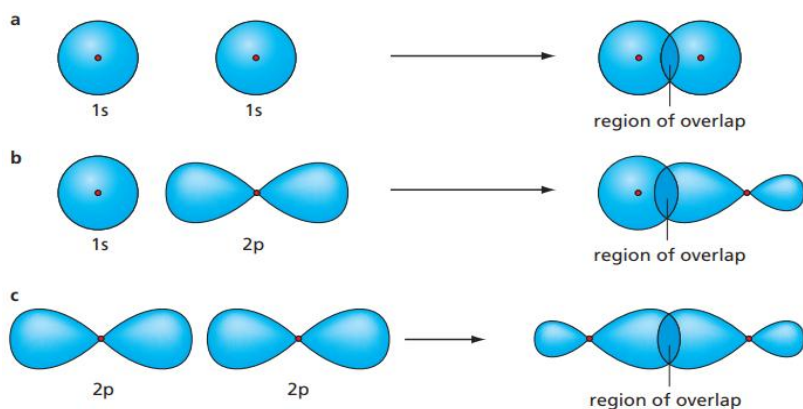
When one s orbital and three p orbitals are hybridised, the hybrids are called **sp³ hybrids**. In sp³ hybrids, each orbital has s character and p character.



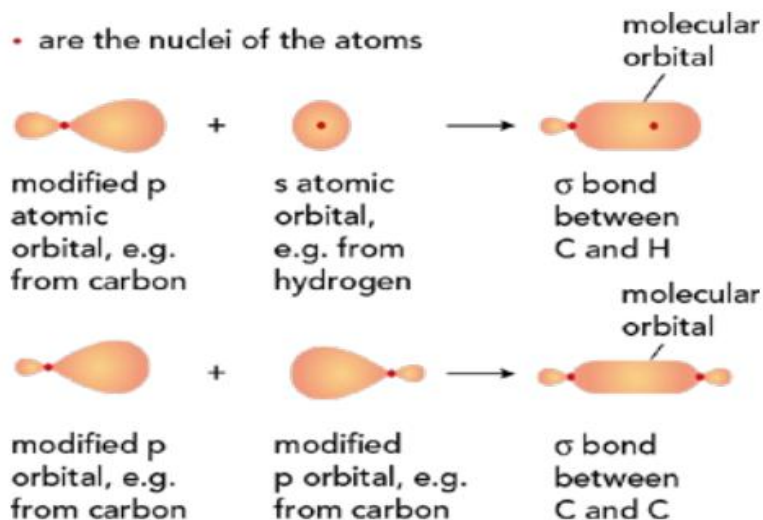
Orbital overlap

A single bond is produced when a pair of electrons is shared between two atoms. The electron pair occupies a molecular orbital formed by the overlap of an atomic orbital on each atom. The atomic orbitals can be s orbitals or p orbitals, or a mixture of the two.

When hybridised orbitals overlap linearly (end-on) we call the bond a **σ bond** (sigma bond).

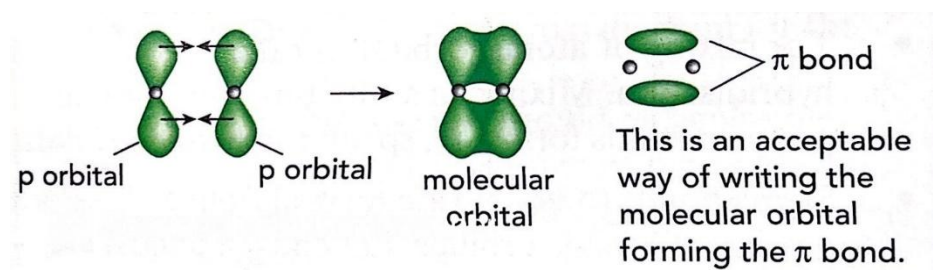


The electron density of each σ bond is symmetrical about a line joining the nuclei of the atoms forming the bond.



Bonds formed by the sideways overlap of adjacent p orbitals above and below the σ bond are called π bonds (pi bonds).

A π bond is not symmetrical about the axes joining the nuclei of the atoms forming the bond.



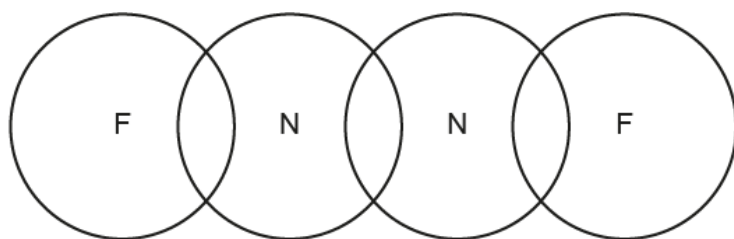
17. A triple bond consists of one sigma (σ) and two pi (π) bonds.
Draw a labelled diagram to show the formation of one pi (π) bond.

[2]

18. The N_2F_2 molecule has a double covalent bond between its nitrogen atoms. This consists of a σ and a π bond.

(i) Complete Fig. 3.2 to show the dot-and-cross diagram for N_2F_2 .
Show outer electrons only.

[2]



(ii) Deduce the hybridisation of the N atoms in N_2F_2 .

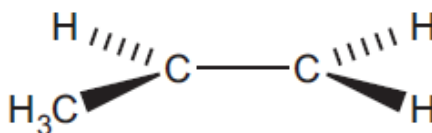
[1]

(iii) Draw a diagram of the π bond between the N atoms in N_2F_2 and describe how it forms.

[2]

19. Complete Fig. 3.2 to show the π (π) bond in L that is formed from orbital overlap.

[1]



15. Which molecule contains a nitrogen atom with sp hybridised orbitals?

A $\text{CH}_3\text{CH}_2\text{NH}_2$

B HNO_3

C HCN

D NH_3

σ and π bonding in H_2 , C_2H_6 , C_2H_4 , HCN and N_2 molecules

20. Covalent bonds can be σ bonds or π bonds.

Complete the following table to show the number of σ and π bonds in a molecule of N_2 and to describe how the orbitals overlap to form σ and π bonds.

[4]

	σ bonds	π bonds
Number of bonds in N_2		
How the orbitals overlap		

21. Describe the covalent bonds present between the carbon atoms in an ethene molecule by completing the following table.

[2]

	π (π)	sigma (σ)
type of orbitals involved in bond		
how the orbitals overlap		

1. The bonding between two atoms of nitrogen in an N_2 molecule involves the hybridisation of atomic orbitals to form sp orbitals.
Which row is correct?

	formation of the σ bond between the nitrogen atoms in N_2	type of orbital which contains the lone pair of electrons on each nitrogen atom in N_2
A	an sp orbital from one atom overlaps with an sp orbital of the other atom	p
B	an sp orbital from one atom overlaps with an sp orbital of the other atom	sp
C	an s orbital from one atom overlaps with a p orbital of the other atom	p
D	an s orbital from one atom overlaps with a p orbital of the other atom	sp

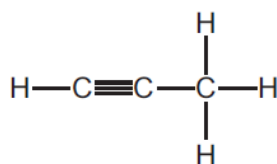
2. The double bond between the two carbon atoms in an ethene molecule consists of one σ bond and one π bond.
Which orbitals overlap to form each of these bonds?

	σ bond	π bond
A	$\text{sp}^2\text{--sp}^2$	p–p
B	$\text{sp}^2\text{--sp}^2$	$\text{sp}^2\text{--sp}^2$
C	$\text{sp}^3\text{--sp}^3$	p–p
D	$\text{sp}^3\text{--sp}^3$	$\text{sp}^2\text{--sp}^2$

3. When considering one molecule of ethene, which row describes both the hybridisation of the atomic orbitals in the carbon atoms and the overall bonding?

	hybridisation	bonding
A	sp^2	4 σ bonds 1 π bond
B	sp^2	5 σ bonds 1 π bond
C	sp^3	4 σ bonds 1 π bond
D	sp^3	5 σ bonds 1 π bond

4. The diagram shows the bonding in a molecule of propyne.

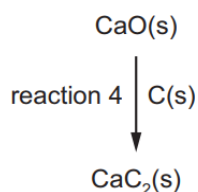


Which types of hybridisation are shown by the carbon atoms in propyne?

- A sp, sp^2 and sp^3
 B sp and sp^3 only
 C sp^2 and sp^3 only
 D sp^2 only

22. Nitrogen molecules, $\text{N}_2(\text{g})$, contain two atoms attracted to each other by a triple covalent bond. Describe how the triple covalent bond forms in a $\text{N}_2(\text{g})$ molecule. Refer to orbital overlap and hybridization in your answer. [3]

23. In reaction 4, calcium carbide, CaC_2 , is formed from CaO .



CaC_2 contains the C_2^{2-} anion. Each carbon in C_2^{2-} is sp hybridised. [1]

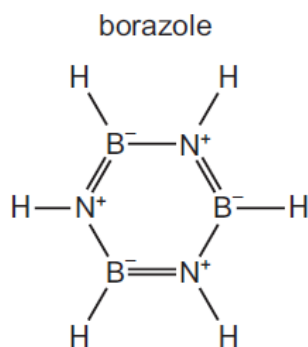
- (i) Describe how sp hybridised orbitals are formed. [1]
- (ii) Sketch a diagram to show how two sp hybrid orbitals can form a sigma (σ) bond. [2]

24. A $\text{C}=\text{C}$ bond in an alkene is made from a σ bond and a π bond.

- (i) Identify the hybridisation of the carbon atoms in a $\text{C}=\text{C}$ bond in an alkene. [1]

- (ii) Draw labelled diagrams to show, in terms of orbital overlap, how the σ and π bonds are made in a $\text{C}=\text{C}$ bond. [2]

5. A structure for borazole, $\text{N}_3\text{B}_3\text{H}_6$, is shown.



Which shape is borazole, and how many π electrons are there in the structure?

6. Propene, hydrogen cyanide and carbon dioxide each contain π bonds.
Which molecules contain two π bonds?

A carbon dioxide and hydrogen cyanide
B carbon dioxide and propene
C hydrogen cyanide and propene
D hydrogen cyanide only

7. NH_3 and HCN react together to form NH_4CN , an ionic compound.
Which row states the number of coordinate bonds and the number of π bonds in one formula unit of NH_4CN ?

	number of coordinate bonds	number of π bonds
A	0	2
B	1	2
C	0	3
D	1	3

Bond energy

Bond energy is the energy required to break one mole of a particular covalent bond in the gaseous state.

Bond length is the internuclear distance of two covalently bonded atoms.

Double and triple covalent bonds are successively shorter than the single covalent bonds.

This is not a complete note. It is to guide you. It is recommended to study the prescribed textbooks along with this material.