The Andromeda Files

An Introduction to the microworld

This problem is an interdisciplinary problem; it is presented here in its original form as well as in its Physics-, Chemistry- and Biology-focused forms.

Intended Learning Outcomes

For more detailed learning outcomes see inside document)

Physics:

- Kinetic theory of gases
- Equilibria
- Condensed phases of matter: bonding, intermolecular forces and structures in the solid phase
- Liquid solutions: dissociation and intermolecular forces; volume and densities

Chemistry:

- Atomic structure and electronic configuration; orbital wave functions; bonding
- Valence Shell Electron Pair Repulsion Theory
- Organic molecules; functional groups, reactivity and isomeric forms

Biology:

- Cellular membranes; cellular structures and organelles
- Prokaryotic and eukaryotic cells; energy requirements
- Connections between cells
- Amino acids and proteins; Primary, secondary, tertiary and quaternary protein structure.
- Fats, carbohydrates and nucleic acids.

KEYWORDS:

Acid-base equilibria, *amino acids*, atomic structure, bonding, *carbohydrates, cellular energy requirements*, *cellular membranes*, *cellular structures/organelles*, *connections between cells*, density, dissociation, electronic configuration, equilibria, *eukaryotic cells, fats, functional groups,* ideal gas law, intermolecular forces, *isomers,* kinetic theory of gases, mean free path, molarities, *molecular representation, molecular structures,* molecules, *nucleic acids,* orbital wave functions, *organic molecules,* phases of matter, predicting physics properties, pressure, *primary/secondary/tertiary/quaternary protein structure, prokaryotic cells, proteins,* solutions (liquids), structure of solids, *Valence Shell Electron Pair Repulsion Theory (VSEPRT),* volume.

Contents

The original form of the problem is a four week (15 credit) module in the IScience programme at the University of Leicester providing part of an introduction to Biology, Chemistry and Physics. The problem may be used as a whole or split into its component parts. Suggested rewordings are provided.

Intended Learning Outcomes (in detail)

By the end of this problem students should be able to:

Physics

- Use the kinetic theory of gases to explain the properties of gases, to explain the concept of pressure, to apply the ideal gas law and to determine the mean free path and mean velocity of a gas particle as a function of temperature.
- Apply the concept of equilibria to chemical and physical processes including acid-base equilibria.
- Explain the physical and chemical behaviour of condensed phases of matter in terms of bonding, intermolecular forces and structure in the solid phase.
- Describe solutions in terms of dissociation and intermolecular forces and to calculate the molarities of solution from masses, volumes and (in some cases) densities.

Chemistry

- Apply the principles of atomic structure, electronic configurations and the concept of orbital wave functions in the context of bonding and make predictions of some physical properties (e.g. magnetism) of simple chemical species based on the above considerations.
- Apply Valence Shell Electron Pair Repulsion Theory (VSEPRT) to determine the geometries of simple molecules.
- Name and draw accurate representations of simple organic molecules, identify functional groups present in those structures and recognise the contribution of the different functional groups to the reactivity of organic species.
- Determine the different isomeric forms of organic structures; be able to label isomers using the appropriate notation and state how different isomers can be distinguished experimentally.

Biology

- Describe the structure and properties of cellular membranes.
- Understand the differences between prokaryotic and eukaryotic cells.
- Identify cellular structures and describe their functions, and type of cells they are found in.
- Detail the proteins which contribute to the cytoskeleton of the cell.
- Understand the energy requirements in the cell and have a basic understanding where this comes from on a cellular level.
- Describe the different types of connections between cells.
- Understand how amino acids form proteins
- Understand how amino acid side chains affect the properties of a protein
- Describe the meaning of Primary, Secondary, Tertiary and Quaternary protein structure,
- Draw the typical chemical structure of Fats, carbohydrates and nucleic acids
- Understand the biochemical role of fats, carbohydrates and nucleic acids

Reading List

The reading list is that provided for the original module. Other equivalent textbooks are available.

Ready to Study

- Sutton, J., ***Biology***. Macmillan Foundations.
- Breithhaupt, J., ***Physics***. Palgrave Foundations.
- Lewis, R. & Evans, W., ***Chemistry***. Palgrave Foundations.
- Trefil, J. & Hazen, R. M., ***Sciences: An Integrated Approach***. Wiley.

Essential

- Burrows, A., Holman, J., Parsons, A., Pilling, G. & Price, G., ***Chemistry^3*****.** Oxford University Press.
- Campbell, N.A. & Reece, J.B., ***Biology***. Pearson.

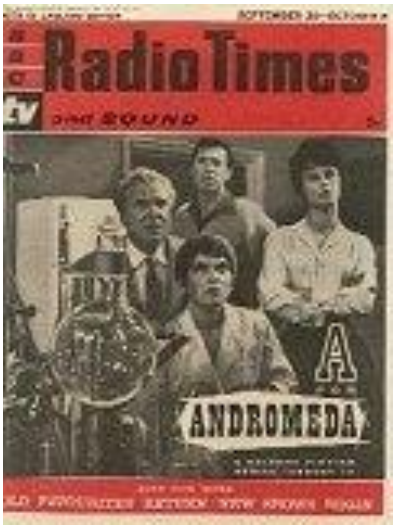
Further

- Atkins, P. & de Paula, J., ***Atkins' Physical Chemistry***. OUP
- Clayden, J., Greeves, N., Warren, S. & Wothers, P., ***Organic Chemistry***. OUP
- Berg, J.M., Tymoczko, J.L. & Stryer, L., ***Biochemistry***. Palgrave.
- Alberts, B., Johnson, A., Lewis, J., Raff, M., Roberts, K. & Walter, P., ***Molecular Biology of the Cell***. Garland Science

Other

- Brown, T.L., LeMay, H.E. & Bursten, E.B., ***Chemistry: The Central Science***. Prentice Hall.
- Housecroft, C.E & Constable, E.C., ***Chemistry: An Introduction to Organic, Inorganic and Physical Chemistry***. Prentice Hall.
- Zumdahl, S.S., ***Chemical Principles***. Houghton Mifflin.
- Tipler, P.A., ***Physics for Scientists and Engineers***. Freeman.

Problem Statement



A for Andromeda was a made-for-TV Science Fiction serial broadcast in 1961. The basic plot is the discovery of a radio message received from a distant civilisation with coded instructions on how to make a living being. Unfortunately the tapes of all but one of the episodes have been wiped so the coded message has been lost. In order to advertise their remake of the series, **TV Remakes Unlimited** decided to publicise the supposed discovery of a "real" coded message received by Jodrell Bank in 1987 which it claimed had been hushed up by the military and government. The code in the original broadcast production was alpha-numeric but it was decided to give the supposedly newly discovered one a glyphic form to make the deciphering more interesting.

To make the problem Statement subject-specific add one of the following paragraphs to the end:

Interdisciplinary:

You must decide what each glyph symbolises and therefore in which order the "message" should be assembled in order to create the life form.

Glyphs: A-M

Physics:

Decide what each glyph symbolizes and the ways in which the different phases of matter are key to living cells.

Glyphs: C, E, F

Chemistry:

Decide what each glyph symbolizes and the extent to which this part of the message is key to the chemistry of life.

Glyphs: A, B, E, G, I, J, K, L, M

Biology:

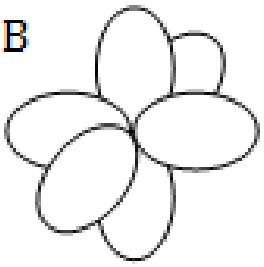
Decide what each glyph symbolizes and hence what aspects of the biological cell are being coded.

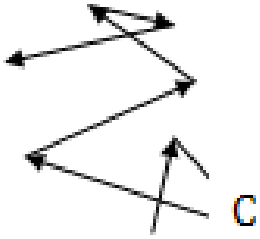
Glyphs: D, H, K

The Glyphs

A

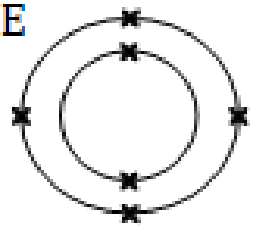
B





C

E



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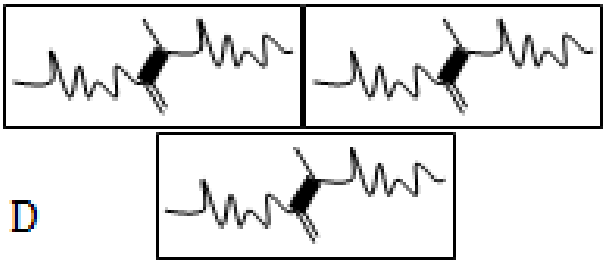
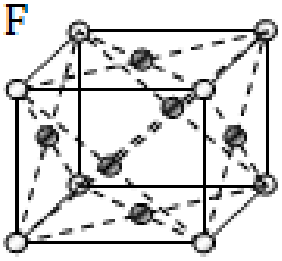


F



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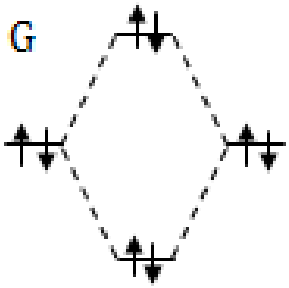

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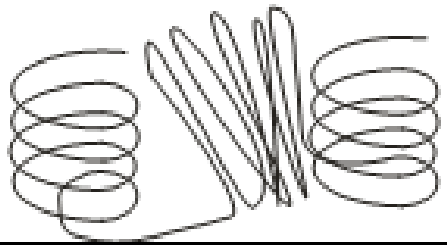
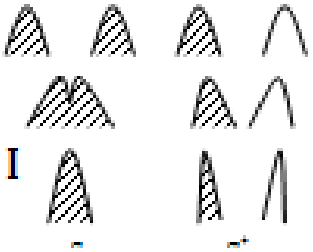


I



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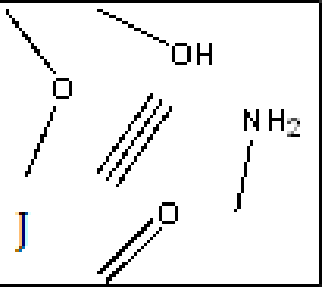

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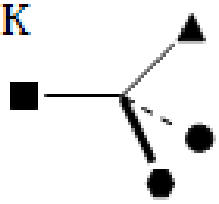
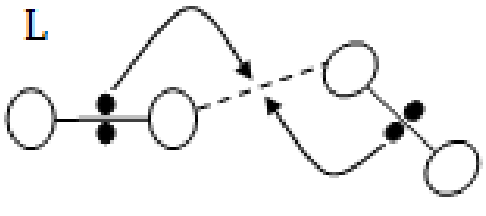


L



sp^3

M

Suggested Deliverables

Extended interdisciplinary problem:

Write an account of what each glyph symbolises and therefore in which order the “message” should be assembled in order to create a life form.

Shorter problems:

- Explain how one or more glyphs is being used as a model of reality
- Explain the role of the entity represented by one or more glyphs in living organisms

Questions for Class Discussion

Physics

1. Most substances are denser in their solid forms than their liquid forms. Ice floats on water which suggests the opposite – why is this the case?
2. Sugar is not an ionic solid so why does it dissolve in water?
3. What happens during a phase transition?
4. Discuss the various types of solid structure and relate differences in these structural types on the atomic scale to differences in physical properties.
5. What are close packed structures? What is the most efficient way of packing oranges into a box? What significance does this have to the structure of some solids?
6. List the units that pressures are commonly expressed in. Create a conversion table for these units.
7. What is a partial pressure?
8. How can we determine the average speed of gas particles?
9. Discuss how gases can move in terms of translation, rotation and vibration. Compare this motion with that of liquids and solids. Why are rotational and vibrational modes of molecules useful to analytical chemists?

Chemistry

1. Which rules govern how atomic (and molecular) orbitals are filled?
2. How can wave theory be used to describe the interaction of atomic orbitals to form molecular orbitals?
3. What is the siginificance of the π and σ labels used for molecular orbitals?
4. What is a molecular orbital?
5. What does a molecular orbital diagram show? How can we predict whether a molecule is paramagnetic or diamagnetic from a molecular orbital diagram?
6. How can the structure of methane be rationalised in terms of molecular orbitals?
7. Why is the π_{2p} molecular orbitals lower in energy than the σ_{2p} in N_2 but the opposite way around in O_2?
8. Why do molecular orbital diagrams of heteronuclear diatomics look skewed?
9. How can the tetrahedral shape of methane be justified?
10. What is hybridization in the context of chemical bonding?
11. Draw diagrams to represent the combination of atomic orbitals that produce sp, sp^2 and sp^3 hybrid orbitals.
12. Why are the C-H single bond lengths in propane, propene and propyne different?
13. What is the significance of bond order in terms of predicting the stability of a molecule? How can MO diagrams be used to calculate bond order?
14. How can we predict the shapes of simple molecules based on electron counting?
15. How do we treat lone pairs of electrons, double and triple bonds when determining molecular geometry?
16. Why do the bond angles of some molecules show deviations from the ideal geometries of the shapes predicted?
17. What are the key differences between alkanes, alkenes and alkynes both in terms of structure (i.e. how we draw them) and in terms of valence bond theory?
18. What common functional groups do we encounter when discussing the chemistry of life? What is the significance of these various functional groups?
19. Why are some molecules described as being left or right handed?
20. How can we measure optical activity in the lab?
21. Why is stereochemistry relevant to the birth defects caused by the drug thalidomide
22. What is a chemical equilibrium? Discuss the significance of equilibrium constants.
23. What is a reaction quotient?
24. Why is the significance of Le Chatelier's Principle?
25. What are the key differences between a strong and weak acid (or a strong and weak base)?
26. What do pH, K_a and pK_a tell us about a solution?

27. Find titration curves for a strong acid-strong base titration, a weak acid-strong base titration and a strong acid-weak base titration. Discuss the key features and try to explain what is happening. How can the pH at any point in these titrations be calculated?
28. What are the key characteristics of buffer solutions?
29. How do buffer solutions work?
30. How can we calculate the pH of a buffer solution if we know the pK_a?
31. What is an electrolytic solution?
32. Why do H^+ and OH^- water have and unexpectedly high limiting ionic conductivities in water?
33. If a neutral solution is heated the pH decreases below 7. Is this solution acidic, neutral or basic?
34. Why is Hydrogen bonding such an important intermolecular interaction?
35. What kind of intermolecular interactions occur in the following systems:
    a) Water,
    b) Iodine (I_2) and
    c) Methyl Chloride (CH_3Cl).

    Discuss the nature and relative strengths of these interactions.
36. Why does water boil at 100 ˚C? (If we look at the trend in H_2A, where A = a group 16 element, we would expect the boiling point to be around -80˚C)

Biology

1. What are the differences between prokaryotic and eukaryotic cells?
2. What are the three types of cytoskeletal structures found in cell, and what are their main functions?
3. List Structures found only in plant cells and their functions
4. Name the different types of Connections between cells, in which type of organisms they occur, and how they function.
5. Describe the theory of endosymbiosis.
6. A key property of living things is energy utilization. Organisms take in energy and transform it to do many kinds of work. Where, at the cellular level, does this energy comes from?
7. Make a list of the most important processes (or kinds of work) that the cell undertakes that utilize this energy.
8. What happens to protein when we eat it?
9. What are typical functions of proteins in the body?
10. What are the four levels of protein structure and their significance?
11. What is an essential amino acid?
12. What factors influence the final structure of a protein?
13. The major components of dietary fats are triglycerides (triacylglycerols). What are these?
14. How are the components of fat used in cells?
15. What is an essential fatty acid. Why is it important?
16. What happens to carbohydrate after it is eaten?
17. Why are sugars needed by cells?
18. What are the parameters that describe the appearance of a helix?
19. What makes up the backbone of DNA?
20. How are the two strands of DNA connected together?
21. What are base pairs and how are they connected to the rest of the DNA molecule?
22. What is a polynucleotide?
23. What is the difference between DNA and RNA?
24. How long are typical strands of DNA?
25. What are some of the functions of nucleic acids in cells?
26. What happens to nucleic acids after they are eaten?
27. Why aren't nucleic acids or nucleotides essential in the diet?

Individual Exercises

Physics

1. At a given temperature, what does the Maxwell-Boltzmann speed distribution curve tell us?

2. Ammonia is an essential compound in the Haber process which is used to synthesise ammonium nitrate (NH_4NO_3). Ammonium nitrate is used in the fertiliser and explosive industry. Large, scale-up production of ammonium nitrate involves the use of ammonia and therefore chemical engineers need to know the effect on the system for safety. If a given sample of 3.50 moles of ammonia gas is isolated (which occupies 5.20L at 47°C) calculate the pressure of the gas (in atm.).

3. The gas pressure in an aerosol can is 2.0 atm at 25°C. Assuming that the gas inside obeys the ideal-gas equation, what would the pressure be if the can was heated to 500°C?

4. A sample of CO_2 gas is initially at standard pressure and temperature (101325 pa and 298 K respectively). It is then compressed to a smaller volume at constant temperature. What effect does this change have on:
   a) The average kinetic energy of CO_2 molecules.
   b) The average speed of CO_2 molecules.
   c) The total number of collisions of CO_2 molecules with the container walls in a unit time.
   d) The number of collisions of CO_2 molecules with a unit area of the container wall per unit time?

5. Give the type of motion and state how many degrees of freedom, are present in:
   a) Xenon
   b) Oxygen

6. Indicate the type of crystal (molecular, metallic, covalent-network, or ionic) each of the following would form upon solidification:
   a) $CaCO_3$
   b) Pt
   c) ZrO_2 (melting point, 2677°C)
   d) Kr
   e) benzene
   f) I_2.

7. Which type (or types) of crystalline solid is characterised by each of the following:
   a) high mobility of electrons throughout the solid,
   b) softness, relatively low melting point,
   c) high melting point and poor electrical conductivity,
   d) network of covalent bonds,
   e) charged particles throughout the solid.

8. What type(s) of intermolecular force is (are) common to:
    a) Xe and methanol (CH_3OH)
    b) CH_3OH and acetonitrile (CH_3CN)
    c) NH_3 and HF?

9. Which member of the following pairs has the stronger intermolecular dispersion forces:
    a) Br_2 or O_2
    b) CH_3CH_2SH or $CH_3CH_2CH_2SH$

10. What type of intermolecular force accounts for the following differences:
    a) CH_3OH boils at 65^{o}C, CH_3SH boils at 6^{o}C.
    b) Xe is liquid at atmospheric pressure and 120K, whereas Ar is a gas.

Chemistry

1. An architect wishes to make a one-hundredth scale model of the new St. Pancras Station. All answers should be express in Standard International units, and using scientific notation, ('standard' or 'exponential' form).
   a) The Champagne bar measures 90 m in length. How long will the champagne bar be in the model?
   b) Twenty thousand litres of blue paint were used to paint St. Pancras station. How many litres will be needed to paint the model?
   c) A Gastro pub has replaced the old Mc Donalds. In the model, the Gastro pub has a volume of 4.56×10^{-3} m^3. If the minimum requirement for space is 8 m^3 per person, how many people will be allowed in the St. Pancras Gastro pub?

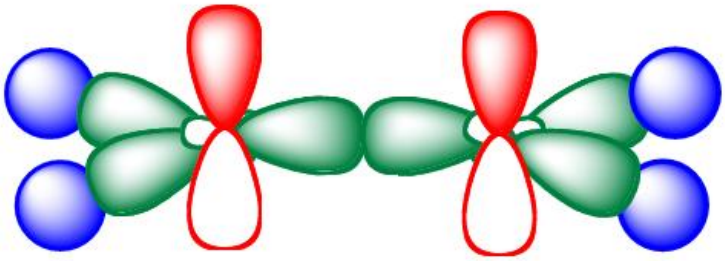
2. Give the Standard International (SI) unit and its abbreviation for each of the following:
   a) Mass
   b) Length
   c) Time
   d) Temperature
   e) Amount of substance
   f) Electric current
   g) Energy
   h) Luminous intensity

3. Convert the following measurements into the units given in brackets. Give your answers in both 'everyday' form and in exponential form.
   a) 6.35×10^{-2} L (cL)
   b) 3.5×10^{-10} g (ng)
   c) 6.54×10^{9} fs (µs)
   d) 150 mL (L)
   e) 3.4 kJ (J)
   f) 25 ºC (K)
   g) 2.4 km (nm)

4. Say which of the following is bigger, and by what multiple?
   a) 2.4 cm or 0.24 m
   b) 1200 mg or 1.2×10^{4} µg
   c) 3.5×10^{5} fs or 3.5 ms
   d) 75 cL or 7.5×10^{-2} L

5. The configuration of electrons surrounding an atoms nucleus will affect its chemical and physical properties. In any atom, the electrons are arranged in different valence shells and orbitals. Sketch the shapes of s, p, and d orbitals.

6. Given below is the bonding orbital diagram of an **ethene** ($H_2C=CH_2$) molecule. Label the **σ and π bond.** (Blue = s, green = Sp^3 orbital, red p orbital).

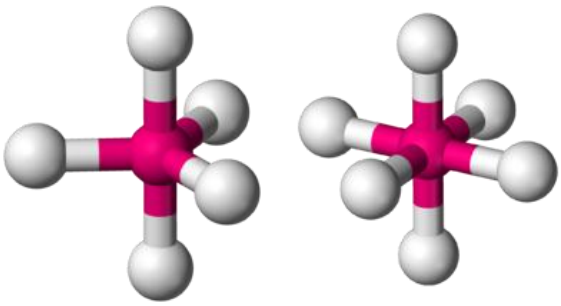


7. The ground state electron configurations of elements are important to chemists. Explain what is meant by the ground state electron configuration and which rules are important in building up this picture, using carbon as an example.

8. Give the ground state electron configurations of:
   a) Carbon
   b) Neon

9. The molecular orbital theory goes a long way in explaining why some molecules exist (e.g. H_2) and why some do not (e.g. He_2).
   a) Explain what is meant by M.O theory using the following terms: Bonding M.O, antibonding M.O
   b) Draw and label a simple molecular orbital diagram for a H_2 molecule.
   c) By reference to the molecular orbital diagram, explain why He_2 is unstable.

10. Give the bond angles present in each of the molecules below.



11. VSEPR theory provides a simple model for predicting the shapes of species.
   a) Define what VSEPR stands for.
   b) Show that VSEPR theory is in agreement with the following molecular shapes:
      BCl_3 → trigonal planar
      $[IF_5]^{2-}$ → pentagonal planar
      $[NH_4]^+$ → tetrahedral
      SF_6 → octahedral
   c) Using VSEPR theory, determine the shape of the following molecules: $BeCl_2$, NH_3, PF_5
   d) Hence, deduce the names of shapes given to each of the above molecules.

Biology

1. Give the three main types of fibres that make up the cytoskeleton. For each type, *describe* two main functions.

2. a) Describe the difference in function between the cis- and trans- face of the Golgi apparatus.
   b) How is this function difference reflected in the location of the Golgi apparatus with respect to other cell organelles?

3. Describe the structural and functional distinctions between rough and smooth endoplasmic reticulum.

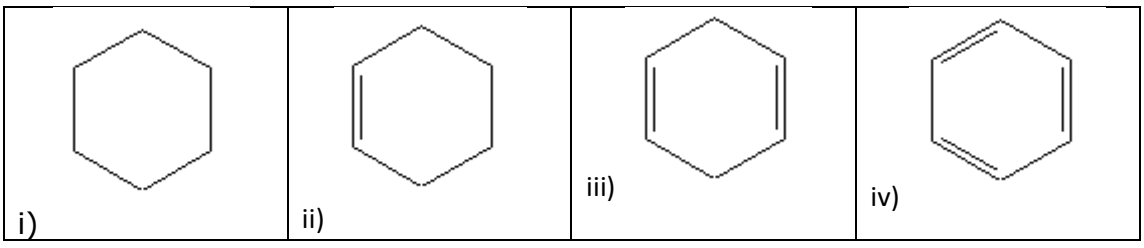
4. Draw a short cartoon strip, with 3 – 5 captioned pictures to show the process of phagocytosis.

5. a) Describe two significant similarities and two differences between chloroplasts and mitochondria.
   b) Explain the characteristics of mitochondria and chloroplasts that place them in a separate category from organelles in the endomembrane system.

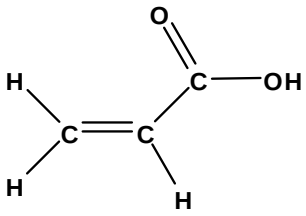
6. a) Where is ribosomal RNA synthesised?
   b) What other type of macromolecule is required to make ribosomes?

7. a) Draw a diagram of a cell membrane, labelling the hydrophilic and hydrophobic parts of the lipid bilayer, and include a channel protein in your diagram.
   b) Describe how aquaporins assist the transport of water molecules across the cell membrane.
   c) Briefly describe the discovery of aquaporin and relate it to the maxim 'chance favours the prepared mind'.

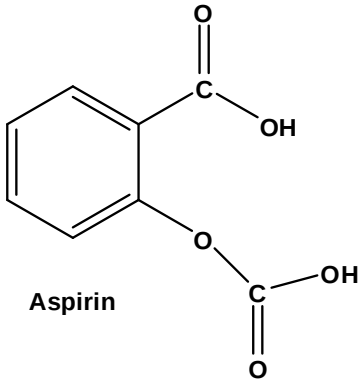
8. Aromatic compounds are important in chemistry and biology since they are found in many naturally occurring molecules. The Huckel 4n + 2 π rule determines whether a compound is aromatic or not.
   a) Benzene is an example of an aromatic hydrocarbon. How many C-C π bonds are present in benzene?
   b) Which of the following molecules is identified as an aromatic hydrocarbon?



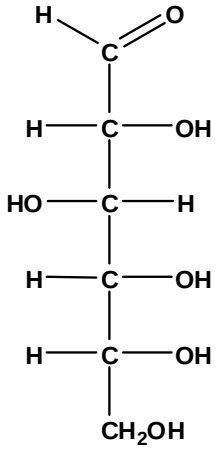
9. Circle and identify the functional groups in the following molecules:



Acrylic acid



Aspirin



Glucose

10. Organic chemists working in the pharmaceutical industry need to know how to synthesise molecules with different functional groups on the active molecules. Below is a list of common functional groups used in pharmaceutical drugs. Draw these functional groups and give an example of each.
    a) Alcohol
    b) Ether
    c) Aldehyde
    d) Ketone
    e) Carboxylic Acid
    f) Ester
    g) Amine

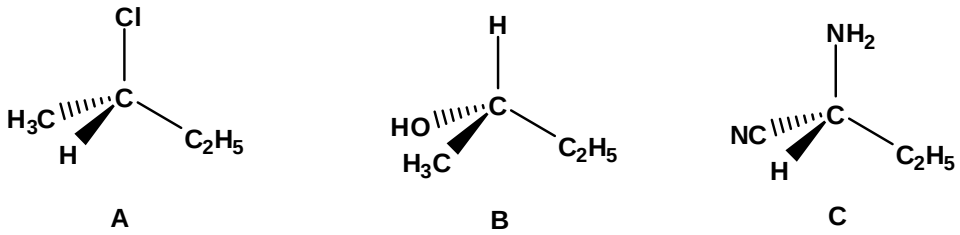
11. Consider the molecule with the condensed structural formula $C_2H_5CH(OH)CH_3$.
    a) Name the molecule
    b) Draw a carbon skeleton representation of the molecule and identify the chiral carbon.

12. Give 3 isomers of C_3H_8O, naming each respective structure according to IUPAC notation.

13. Name the 3 different classes of structural isomers, giving an example in each case.

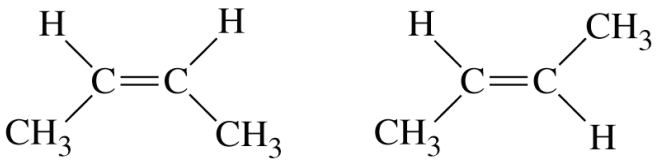
14. Determine which of the following compounds will be chiral. If chiral identify the stereogenic centre.
    a) 2-Bromopentane
    b) 4-Heptanol
    c) 2-methyl-1-butanol
    d) 1-chloro-2-methylbutane
    e) 2-propanol

15. Enantiomers can be distinguished via there configuration, hence assign R,S configurations to the following molecules. (You may use molecular models to help you).



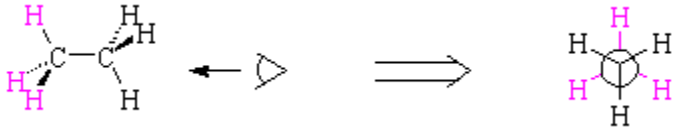
16. a) Draw and label a systematic representation of a polarimeter.
    b) With reference to the above diagram. Explain how optically active molecules can be distinguished via the above technique.

17. Alkenes exist as geometrical isomers due to restricted rotation about the C-C double bond. They have different physical and chemical properties and are therefore separable. In the pharmaceutical industry this can mean the difference between a drug curing or killing a patient. State, with reasons, which of these geometrical isomers has the lowest energy conformation.



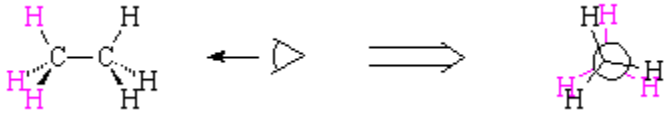
18. When organic chemists try to predict a mechanism for a reaction, the conformation of the reactant species might be of importance. This is due to the fact that during nucleophilic attack, the nucleophile will prefer to attack the reactant in its lowest energy conformation. Using ethane as an example explain which of these has the lowest conformation?

    a)



    or

    b)



19. Haemoglobin is an important biological transporter of oxygen. It is a protein consisting of four subunits, which alters its conformation slightly depending on the partial pressure of oxygen, and in so doing, allows the reversible bonding of oxygen to it. By reference to the molecule haemoglobin, describe the primary, secondary, tertiary and quaternary structure of proteins.

20. A region along one DNA strand has this sequence of nitrogenous bases:

5' – TAGGCCT – 3'.

a) Draw a structure for this DNA strand which shows how the phosphates and sugars are connected to the first three bases TAG.
b) List the base sequence along the other strand of the molecule, clearly indicating the 5' and 3' ends.
c) Write a flow chart to show how a strand of DNA codes for a length of polypeptide.

21. Consider the molecule ethanol. Using the program chem draw to help you (this is CFS software), give the following structures for ethanol:
a) A condensed structural formula
b) A carbon skeleton
c) A representation of the molecule in 3-dimensions
d) A dot and cross diagram of the molecule
e) A space filling model

22. Different representations of molecules provide scientists with different information, which will be relevant in different contexts.
a) Give the molecular formula of glucose
b) Give the molecular formula of fructose
c) Show the carbon skeletons of each of the open ring structures of each of the above molecules.
d) By reference to this example describe one piece of additional information that can be obtained by use of a carbon skeleton.
e) Describe the structural difference between starch and cellulose.
f) What further information is obtained by use of a three dimensional structure that would not be obtained if a carbon skeleton were used.