TESTING AND IMPROVING STUDENTS' UNDERSTANDING OF THREE-DIMENSIONAL REPRESENTATIONS IN CHEMISTRY

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ABSTRACT

Three-dimensional visualisation is an important skill in chemistry but one in which many students experience difficulty.

The main aims of this research were to identify the nature, extent and particularly the reasons for university students' difficulties in three-dimensional thinking and to devise teaching strategies for overcoming them. The research was restricted to the simpler aspects of three-dimensional thinking; it dealt only with rotation and reflection of simple molecules.

The component steps required for the solution of three-dimensional problems were identified, and students' competence in these steps was tested. Pretest results showed that the students initially had poor visualisation skills. The main reasons for their difficulties were identified to be: (a) inability to visualise the three-dimensional structures of molecules, using the depth cues; (b) lack of precise understanding of the meaning of the phrases used in the questions (such as rotation about the X-axis; reflection in the XY plane); (c) inability to visualise the orientation of the axes and planes and of the positions of the atoms after an operation.

A ninety minute remedial instruction programme on those aspects which caused difficulty was found to be enough, as shown by an analysis of covariance, to improve the students' visualisation skills very significantly ($p < 0,01$).

DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the degree of Master of Education in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

H. P. Tuckey

24th day of May ,19 89

In Memory of my Father
Grierson Tuckey
1914 - 1982

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CONTENTS

INTRODUCTION

This research project involved the identification and rectification of students' difficulties in three-dimensional thinking in chemistry. Only the simpler aspects of three-dimensional thinking were studied - those involving rotation and reflection. There were three main aspects to this research. These were:

(a) the identification of the nature and extent of students' difficulties in three-dimensional thinking;
(b) an investigation into the factors which affect students' ability in three-dimensional thinking;
(c) the rectification of these difficulties by remedial instruction.

In Chapter 1 each of the above aspects is considered, and the literature on each aspect is reviewed.

In Chapter 2 the structure of the present research is presented and discussed.

There are three main stages to this research. The first stage involved the design and administration of pretests to students and the analysis of the answers. This was done to identify the nature and extent of students' difficulties concerning visualisation of the effects of the operations of rotation and reflection upon diagrams of molecules, and the reasons for these difficulties. The design of the test items used in the research is discussed in Chapter 3. In Chapter 4 the results of the pretests are presented and analysed statistically.

The second stage involved the design and administration of remedial instruction on each component skill that caused difficulty in the overall task of visualising the effects of rotation and reflection upon diagrams of molecules. The remedial instruction programme is discussed in Chapter 5.

The last stage involved the design and administration of post-tests and the analysis of the answers to pretests and post-tests to assess the effectiveness of the remedial instruction programme. This aspect is covered in Chapter 6.

In conclusion, Chapter 7 contains a review of the research, its main findings and recommendations for further research.

CHAPTER 1

REVIEW OF THE LITERATURE ON THREE-DIMENSIONAL VISUALISATION

1.1. Introduction

This research project involves the identification and rectification of students' difficulties in three-dimensional thinking in chemistry. Four main aspects concerning this topic will first be discussed. These are:

(a) a review of the importance of three-dimensional thinking in chemistry;
(b) a consideration of the factors affecting students' ability in three-dimensional representation;
(c) a description of the methods that have been made use of for the identification of the nature and extent of students' difficulties in three-dimensional representation;
(d) a discussion of attempts to rectify these difficulties by remedial instruction.

In this chapter each of the above aspects will be considered, and the literature on each aspect will be reviewed.

1.2. Three-dimensional thinking in Chemistry

Three-dimensional thinking is a skill which is needed throughout much of chemistry. Many methods have been devised for representing on paper (i.e. for representing two-dimensionally) the three-dimensional structures of molecules and crystals; all these methods make use of cues to denote relative depth. In this section the educational and chemical aspects of three-dimensional visualisation will be discussed.

1.2.1. Types of learning in chemistry

The content of chemistry may be divided into five categories, called objects of learning (Gagne, 1977). The objects of learning may be defined as "the things we want students to learn" (Bell, 1978, p. 108). The five objects are facts, concepts, principles theories and skills. Each of these will now be examined in turn.

(a) A fact is "an event that has occurred and been recorded with no disagreement among the observers" (Farmer and Farrell, 1980, p. 76). For example, the statement that the melting point of sodium chloride is 801°, is a fact.

(b) A concept is a classification of ideas, objects or events into a set with common essential characteristics. An element, an acid and a pressure are examples of concepts.

(c) A principle or law involves relationships between concepts. The relationship found between pressure and volume of a gas - that the pressure is inversely proportional to volume for a given amount of gas at constant temperature - is an example of a law (Boyle's law). A law summarises the observed facts (Gillespie, Humphreys, Baird and Robinson, 1986).

(d) A theory is a model that enables us to better understand our observations. The theory that provides an explanation of Boyle's law, for example, is the kinetic molecular theory (Gillespie *et al*, 1986).

(e) Intellectual skills are those operations and procedures which are essentially independent of content. Many intellectual skills can be specified by sets of rules and instructions or by ordered sequences of specific procedures called algorithms. Skills are learned through demonstration and practice. Development of complex skills can be guided by training first in the prerequisite simpler skills. The skill of graphing, for instance, requires the simpler skills of counting, measuring and using a ruler. Students may be considered to have mastered a skill when they can correctly solve different types of problems requiring the use of that skill or when they can apply the skill in various situations (Bell, 1978). The achievement of skill competence can be tested by observation and evaluation of performance.

Among the skills a student is expected to acquire in chemistry are communicative skills, organisational skills, mathematical skills, reasoning skills, problem solving skills and visualisation skills. Skill development seems to enhance growth in conceptual understanding. Concepts are generally the vehicles by which intellectual skills are learned; while skills form a framework on which concepts can be attached (Sund and Trowbridge, 1973).

1.2.2. Types of three-dimensional thinking required in chemistry

Three-dimensional thinking is the subject of my research and hence a review of the various types of three-dimensional thinking required in chemistry will now be given. Three-dimensional concepts are required in three main branches of chemistry: shapes of atomic and molecular orbitals; the arrangement of atoms in molecules; and the arrangement of atoms, molecules and ions in crystal lattices. The discussion that follows focuses on the three-dimensional concepts and representations encountered in undergraduate chemistry. The representations are the ones found in chemistry textbooks used by undergraduate chemistry students. These texts include Brady and Humiston (1978); Huheey (1978); Fessenden and Fessenden (1982); Solomons (1982); Norman and Waddington (1983); Atkins (1986); Gillespie et al (1986) and Morrison and Boyd (1987).

1.2.2.1. Shapes of atomic and molecular orbitals

Atoms contain electrons which are arranged in s-, p-, d- and f-orbitals. These orbitals have different shapes, for example an s-orbital is spherical and a p-orbital is dumbbell shaped, as shown in Figure 1.1 below.

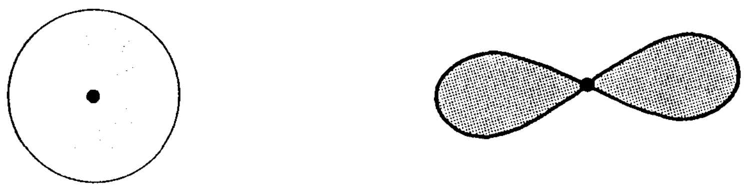


Figure 1.1. Atomic orbitals
(a) an s-orbital (b) a p-orbital

Molecular orbital theory states that when bonds are formed by the overlapping of atomic orbitals, molecular orbitals are formed. For example, two s atomic orbitals can overlap to form an s-s molecular orbital. An s atomic orbital and a p atomic orbital can overlap to form an s-p molecular orbital. Two p atomic orbitals can overlap head on to form a sigma p-p molecular orbital, or sideways to form a pi p-p molecular orbital. These molecular orbitals are represented in Figure 1.2 below.

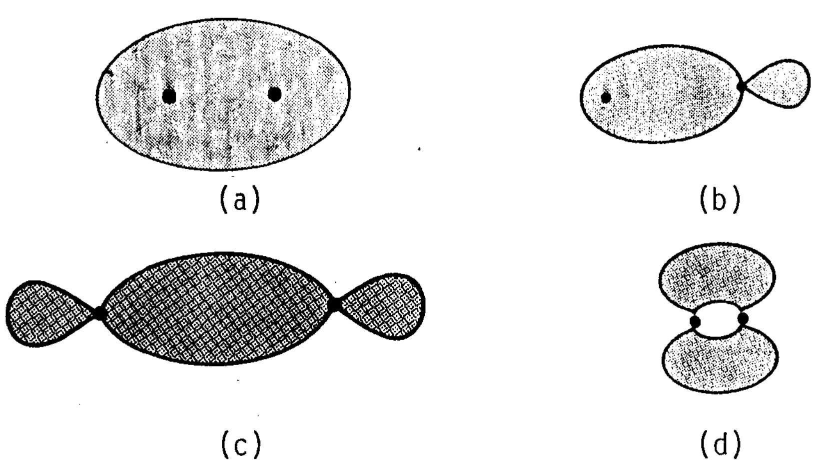


Figure 1.2. Molecular orbitals
(a) s-s molecular orbital (b) s-p molecular orbital
(c) sigma p-p molecular orbital (d) pi p-p molecular orbital

1.2.2.2. Shapes of molecules

The shapes of molecules can be predicted using either the theory of hybridisation of atomic orbitals or the valence shell electron pair repulsion theory.

According to the theory of hybridisation, non-equivalent atomic orbitals can hybridise to give a set of equivalent hybrid orbitals. The orientation of the hybrid orbitals determines the geometry of the molecule or ion. The valence shell electron pair repulsion theory considers the valence electrons around the central atom of a molecule, which may be bonding pairs or lone pairs of electrons. Due to electrostatic repulsion between the negatively charged electrons, regions of high electron density assume positions as far away from each other as possible. The molecular structure therefore depends on the arrangement of the lone pairs and the bonding pairs in the molecule. Both hybridisation and valence shell electron pair repulsion theory predict that organic and inorganic molecules and complexes have specific shapes and bond angles. They may be octahedral, trigonal bipyramidal, tetrahedral, square planar, trigonal planar, linear, angular (120°), angular (109,5°), trigonal pyramidal, square pyramidal, seesaw shaped or T-shaped.

Consider for example the ammonia molecule, NH_3. According to hybridisation theory, the nitrogen atom is sp^3 hybridised, as shown in Figure 1.3 below. The hydrogen nuclei are located at three corners of a tetrahedron; the fourth corner is occupied by an unshared pair of electrons.

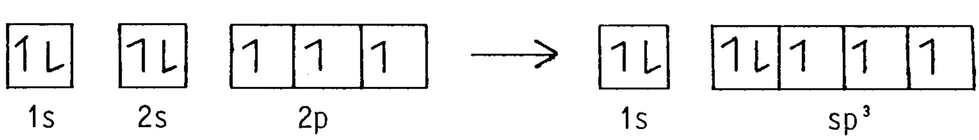


Figure 1.3. Hybridisation of the nitrogen atom in the ammonia molecule

The molecule has one lone pair and three bonds; there are thus four regions of high electron density. Valence shell electron pair repulsion theory predicts a tetrahedral arrangement of the electron pairs. Since one region of electron density is a lone pair, the molecule is trigonal pyramidal, as shown in Figure 1.4.

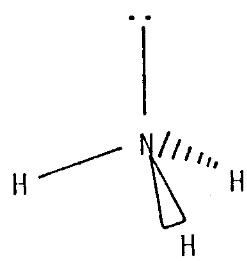


Figure 1.4. Ammonia molecule

The branch of chemistry which deals specifically with the three-dimensional structure of molecules is stereochemistry. Stereochemistry is concerned with four types of isomerism; namely structural, conformational, geometric and optical isomerism. We will consider each of these types of isomerism in turn.

a) <u>Structural isomerism</u>

Structural isomers are compounds that have an identical molecular formula but different structural formulae. This means that they have the same kinds and numbers of atoms but the atoms are arranged differently. Structural isomerism can involve different arrangements of the carbon skeleton, called skeletal isomerism. For example, butane and methylpropane both have the molecular formula C_4H_{10}, but their carbon skeletons are different, as shown in Figure 1.5 below.

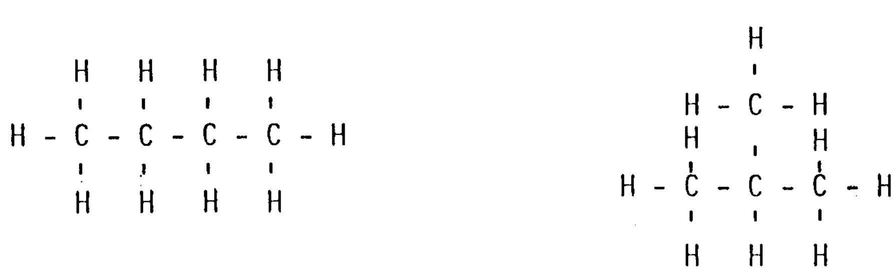


Figure 1.5. Structural isomers
(a) butane (b) methylpropane

Structural isomerism can also involve different positions of a functional group. This is sometimes referred to as positional isomerism. Consider for example the isomers of bromobutane, C_4H_9Br, represented in Figure 1.6 below. The two isomers represent 1-bromobutane and 2-bromobutane.

$CH_3CH_2CH_2CH_2Br$ $\qquad\qquad$ $CH_3CH_2\underset{\substack{|\\ Br}}{C}HCH_3$

Figure 1.6. Positional isomers.
(a) 1-bromobutane (b) 2-bromobutane

Another type of structural isomerism involves functional isomers. Here the functional group differs. As an example consider the isomers of C_2H_6O represented in Figure 1.7 below. The first compound is an alcohol with the functional group OH, while the second is an ether with functional group C-O-C.

CH_3CH_2OH $\qquad\qquad$ $CH_3\text{-}O\text{-}CH_3$

Figure 1.7. Functional isomers
(a) ethanol (b) dimethyl ether

b) <u>Conformational isomerism</u>

Rotation about carbon-carbon single bonds will result in an infinite number of atomic arrangements called conformations. The two extreme forms are the staggered and eclipsed forms, represented for ethane in Figure 1.8 below.

Figure 1.8. Ethane
(a) eclipsed conformation (b) staggered conformation

In cycloalkanes with six-membered puckered rings, conformations can take either the chair form or the boat form, represented for cyclohexane in Figure 1.9 below.

Figure 1.9. Cyclohexane
(a) chair conformation (b) boat conformation

c) Geometrical isomerism

In general, free rotation around carbon-carbon double bonds is not possible since this would involve the breaking of a pi bond. This lack of rotation gives rise to diastereomers called geometric isomers. The configurations of the geometric isomers of 2-butene are represented in Figure 1.10 below. These two isomers represent cis- and trans-2-butene respectively.

Figure 1.10. 2-butene
(a) cis-2-butene (b) trans-2-butene

d) Optical isomerism

Optical isomers are molecules that have the same formula but possess structures that are non-superimposable mirror images of each other; the two isomers are called enantiomers. In organic chemistry, optical isomerism is due to the presence of a chiral carbon atom. A chiral carbon atom occurs when the carbon is bonded to four different atoms or groups of atoms. Consider, for example, the isomers of lactic acid represented in Figure 1.11. The molecules concerned may be rotated in any direction, but cannot be superimposed. They are non-superimposable mirror images of each other. They are found to rotate plane-polarised light in opposite directions.

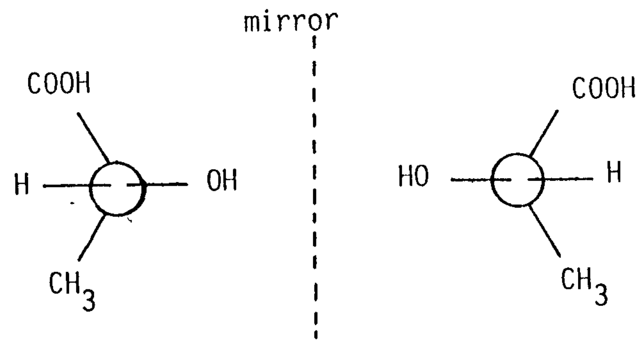


Figure 1.11. Lactic acid

1.2.2.3. Three-dimensional structures of crystals

Crystalline solids have a regular periodic arrangement of their atoms, ions or molecules, and are said to have a lattice structure. That part of the lattice that will generate the entire lattice if it is repeated in three dimensions is called a unit cell. A unit cell is a parallelepiped whose size and shape are defined by the lengths of three axes (a, b and c) and the angles (α, β and γ) between the axes, as shown in Figure 1.12 below.

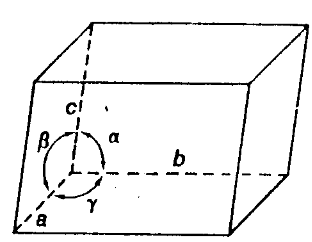


Figure 1.12. A unit cell

Unit cells must take one of seven shapes. The shape can be cubic, tetragonal, orthorhombic, monoclinic, triclinic, hexagonal or rhombohedral. Examples of each type of system are shown in Table 1.1.

Table 1.1

Unit cells of the seven crystal systems

system			example
cubic	a = b = c	$\alpha = \beta = \gamma = 90°$	$NaC\ell$
tetragonal	a = b ≠ c	$\alpha = \beta = \gamma = 90°$	TiO_2
orthorhombic	a ≠ b ≠ c	$\alpha = \beta = \gamma = 90°$	$HgC\ell_2$
monoclinic	a ≠ b ≠ c	$\alpha = \gamma = 90°,\ \beta \neq 90°$	$KC\ell O_3$
triclinic	a ≠ b ≠ c	$\alpha \neq \beta \neq \gamma \neq 90°$	$CuSO_4 \cdot 5H_2O$
hexagonal	a = b ≠ c	$\alpha = \beta = 90°,\ \gamma = 120°$	ZnS
rhombohedral	a = b = c	$\alpha = \beta = \gamma \neq 90°$	$A\ell_2O_3$

Variations in the number and location of the lattice points in these seven unit cells give rise to fourteen types of space lattices. In some of these, lattice points are found only at the corners of the unit cell, and these are called primitive lattices. In others, the points of the lattice occur at the corners as well as the centres of some or all of the faces of the unit cell, and these are face-centred or base-centred lattices. In still others, the points of the lattice are found at the corners as well as the centre of the cell, forming body-centred lattices. The fourteen types of lattice are referred to as Bravais lattices. Cubic lattices can be primitive, face-centred or body-centred. Tetragonal lattices can be primitive or body-centred. Orthorhombic lattices can be primitive, body-centred, face-centred or base-centred. Monoclinic lattices can be primitive or base-centred. Only one arrangement is possible for hexagonal, triclinic and rhombohedral lattices. As an example consider the zinc blende structure, ZnS, represented in Figure 1.13 below. The anions are located at the lattice points in a face-centred cubic unit cell.

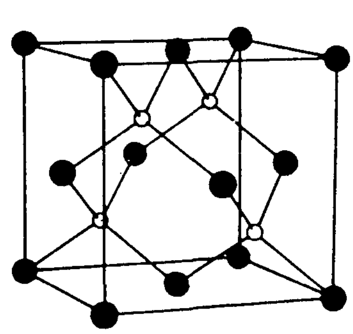


Figure 1.13. Unit cell of zinc blende

1.2.2.4. Symmetry

Ideas about symmetry are important in studies of atomic, molecular and crystal structure. The basic principles of symmetry are made use of in quantum mechanics, spectroscopy and structural determinations by X-ray, neutron and electron diffraction. Five types of symmetry elements are used to describe the symmetry of molecules. These are: centre of symmetry, proper rotation axis, mirror plane, improper rotation axis and the identity element. Each of these symmetry elements has a symmetry operation associated with it. The symmetry elements and the associated operations are described in Table 1.2.

Table 1.2

The symmetry elements and associated operations

element	operation
centre of symmetry (or inversion centre)	a projection through the centre of symmetry to an equal distance on the other side of the centre
proper rotation axis	an anticlockwise rotation about the axis
mirror plane	reflection across the mirror plane
improper rotation axis	combined operation of a rotation followed by reflection across a mirror plane
identity element	an operation corresponding to a rotation of 360° about any axis

1.2.3. Representations and cues used to denote depth in diagrams

All the three-dimensional concepts mentioned in the previous section may need to be represented in two dimensions on paper. There are many ways in which three-dimensional objects encountered in everyday life have been represented two-dimensionally on paper, and theories relating to the mechanism of three-dimensional visualisation from two-dimensional drawings have also been advanced. In addition, chemists have made use of various types of special representations to meet their own needs; they have used cues to denote depth. In this section, the theories on three-dimensional visualisation will first be discussed. Then the various types of representation that chemists make use of to represent the three-dimensional structures of molecules etc. will be considered, together with an explanation of the cues made use of in each representation.

The representations that have been made use of are: ball and stick formulae, dimensional formulae, Newman projections, Sawhorse projections and Fischer projections.

1.2.3.1. Theories on the mechanism of three-dimensional visualisation

An early theory of three-dimensional visualisation was advanced by Berkeley in 1709, and later by Von Helmholtz (Johansson, 1975). According to this theory, the two-dimensional image on the retina is interpreted three-dimensionally by a number of cues, such as the binocular disparity in the images seen by the two eyes, and the size of the image.

Goodman (1968) holds that two-dimensional representations consist of a set of symbols which have to be read, and the ability to do this has to be acquired. According to Gibson (1971) a representation of an object succeeds if it reflects the same structural information to the eye as the object represented. Confusion in three-dimensional visualisation may arise due to the fact that, while many components of a picture bear an obvious relationship to the objects represented, there are also sources of information telling the observer that the picture is flat (Gibson, 1951; Hagen, 1974).

French (1951) and Lohman (1979) identify three factors involved in three-dimensional visualisation. The first is that of spatial relations. This involves the ability to perceive spatial patterns accurately and to compare them with each other. The second factor, spatial orientation, involves the ability to imagine how a representation will appear from a different perspective. Finally, the visualisation factor involves the ability to comprehend imaginary movements in three-dimensional space or to manipulate objects in the imagination.

Some theories of three-dimensional visualisation emphasise the role of the artistic devices or cues which are used to portray depth in diagrams (Gibson, 1966; Seddon, Tariq and Dos Santos Veiga, 1984). The task of visualising the effect of a particular transformation amounts, in essence, to the understanding of each of these depth cues and to knowing how they change as a result of the transformation.

1.2.3.2. Ball and stick formula

In a ball and stick model of a molecule, atoms are represented by balls and the bonds between the atoms are represented by sticks. When this model is drawn in two dimensions, circles and lines are made use of to represent the atoms and the bonds between the atoms respectively. This representation normally makes use of three cues; overlap (or superposition), foreshortening of lines and distortion of angles. Other cues such as relative size and shading or tone cues are sometimes included. Each cue will now be considered in turn.

a) Overlap

The overlap cue is used to show which of any two atoms is further away. Overlap is represented by drawing a line that goes into an atom. To illustrate this, consider Figure 1.14 below. The line from atom B is seen to overlap atom A. Atom A is therefore further away from the viewer than atom B.

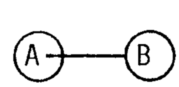


Figure 1.14. The overlap cue

b) Foreshortening of lines

Foreshortening of lines is used as a cue to indicate those atoms in a diagram of a molecule that are not in the plane of the paper. Consider for example the molecule represented in Figure 1.15 (a) below, in which all the bonds have the same length. All the atoms are in the plane of the paper, and all the bonds are drawn the same length. Figure 1.15 (b) shows the same molecule but with atom D not being in the plane of the paper; the bond joining atom D to atom A will then be drawn shorter than the other bonds.

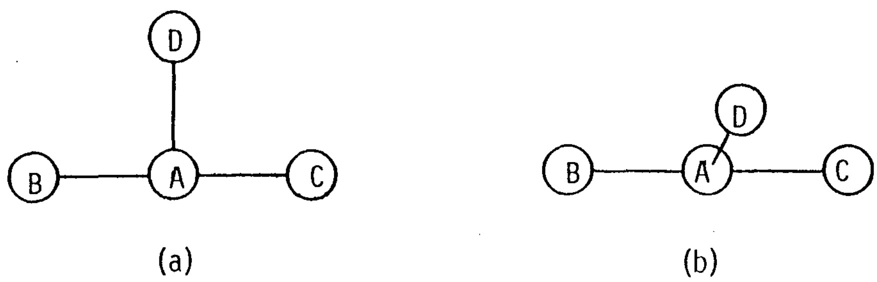


Figure 1.15. Foreshortening of lines

c) Distortion of angles

Distortion of angles is another cue used to denote depth in diagrams; here an angle is drawn a different size from the size it is in the molecule. As an example consider the symmetrical T-shaped molecule represented in Figure 1.16 below. In diagram (a) all the atoms are in the plane of the paper. In diagram (b) atom D is not in the plane of the paper, and the angles between D and other atoms are shown distorted. In this case it is not possible to tell from the diagram what the angles BAD and CAD are in reality.

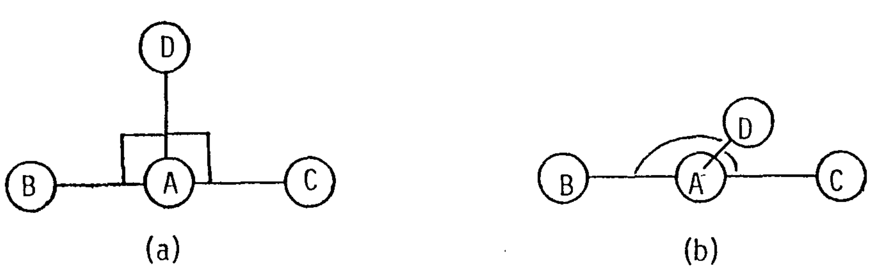


Figure 1.16. Distortion of angles

d) Relative size

Relative size is another cue sometimes used to denote depth in diagrams. Atoms which are closer to the viewer are represented by larger circles, and atoms which are further away are represented by smaller circles. As an example consider the molecule represented in Figure 1.17 below. In diagram (a) both atoms are in the plane of the paper, and are represented by circles of the same size. In diagram (b), however, one atom is closer to the viewer than the other, and is therefore represented by a larger circle.

Figure 1.17. Relative size

e) Tone cues

Sometimes parts of a representation are shaded to indicate the way in which light from a certain source falls on the molecule. As an example consider the molecule represented in Figure 1.18 below. Areas where less light falls are shaded.

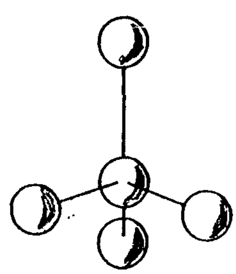


Figure 1.18. Tone cues

1.2.3.3. Dimensional formulae

Another way of representing a molecule is by a dimensional formula. This is a more abstract representation than the ball and stick formula. Bonds are represented in three ways, as illustrated in Figure 1.19 below. Bonds coming out of the plane of the paper are represented by a wedge, ◁, bonds going into the plane of the paper are represented by dashes, ||||| , and bonds in the plane of the paper are represented by lines, ——— .

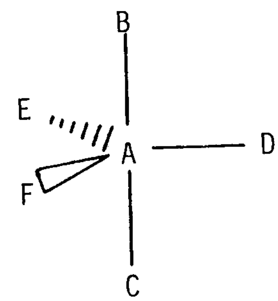


Figure 1.19. Dimensional formula

1.2.3.4. Newman projections

A Newman projection is an end-on view of two atoms in a molecule. The bond joining these two atoms is hidden. Consider for example the ethane molecule, C_2H_6, represented in Figure 1.20 below. The three bonds attached to the front carbon atom appear to go to the centre of the projection, and the three bonds of the rear carbon atom are only partially shown. The overlap cue (see page 15) is incorporated only as far as the front carbon is concerned. The back carbon atom is hidden totally.

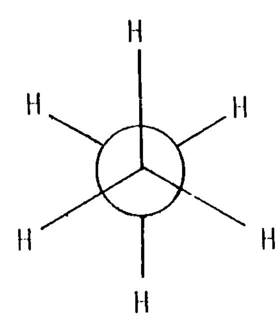


Figure 1.20. Newman projection

1.2.3.5. Sawhorse projections

The Sawhorse projection is used to represent conformations of organic molecules. Consider, as an example, the ethane molecule represented in Figure 1.21. The line joining the carbon atoms comes out of the plane of the paper, while the hydrogen atoms are in the plane of the paper at each end of the projection. Diagrams (a) and (b) represent the eclipsed and staggered forms of ethane respectively.

Figure 1.21. Sawhorse projections of ethane
(a) eclipsed conformation (b) staggered conformation

1.2.3.6. Fischer projections

A Fischer projection is a shorthand and more abstract way of representing either a ball and stick formula or a dimensional formula. There are no depth cues and the convention must be learned. In a Fischer projection, the molecule is drawn completely stretched out in the plane of the paper with all substituents eclipsed, regardless of any preferred conformation. Each horizontal line represents a bond coming towards the viewer, while the vertical line represents bonds going away from the viewer. Consider for example the representation of glyceraldehyde in Figure 1.22 below. The dimensional formula is shown in diagram (a). Diagram (b) shows the Fischer projection of this molecule.

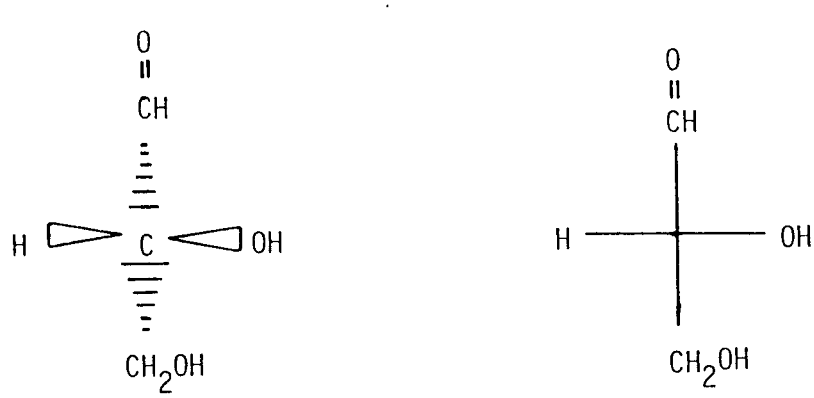


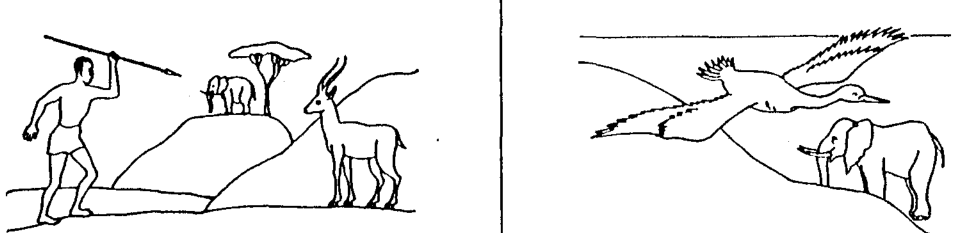
Figure 1.22. Glyceraldehyde
(a) dimensional formula (b) Fischer projection

1.3. Review of the literature on the identification of problems encountered in three-dimensional thinking

In the previous section some important aspects of three-dimensional visualisation were discussed. The types of three-dimensional thinking required in chemistry, and the representations and cues used in chemistry, were reviewed. In this section the tests that have been developed to identify problem areas in three-dimensional visualisation will be considered. Some of these tests focus on the general skill of three-dimensional visualisation, and some focus on the representations and cues used in chemistry.

1.3.1. General tests of three-dimensional visualisation

One of the earliest tests of depth perception was developed by Hudson (1960) using eleven outline drawings and one photograph, representing horizontal and vertical space. Two of the diagrams are shown in Figure 1.23 below. In these diagrams the relative size and overlap cues are used.



a) What do you see? b) What is the man doing? c) Which is nearer the man, the elephant or the antelope?	a) What do you see? b) Which is nearer the man, the elephant or the bird?

Figure 1.23. Examples of items on Hudson's test (Hudson, 1960, p. 186-187)
(a) horizontal space (b) vertical space

Several criticisms of this test have been made. As Hudson himself points out, his drawings are oversimplified. Perspective cues in outline drawings tend to be "symbolic and unrealistic" (Hudson, 1960, p. 202). In addition, the questions involve the concept of nearness; but it is not clear whether the concept of nearness is with reference to the scene or the drawing. Jahoda and McGurk (1974a) criticise Hudson's test further. One of the questions (Question b, see Figure 1.23) on each picture involving vertical space refers to a man, but no man appears in the drawings. Thus the subject has to guess the location of the man. The test is badly constructed, since in all the drawings on horizontal space the antelope is nearer the man, while in all the vertical space drawings the bird is nearer the man. Thus the subject may give the same response to all the questions. A well-designed test should avoid a regular pattern of responses (Sund and Trowbridge, 1973; Bell, 1978). Jahoda and McGurk (1974b), replicating Hudson's work, found that subjects became unfriendly and suspicious as the test progressed, because the same questions were repeatedly asked for each picture. The scoring method used by Hudson is not clear, and others who have employed his test (Mundy-Castle, 1966; Deregowski, 1968; Kilbride, Robbins and Freeman, 1968) have used different methods.

Jahoda and McGurk (1974a, 1974b, 1974c) developed a test using pictures of adult and child figures. The pictures contain the depth cues of relative size and elevation of figures within the pictorial frame. Subjects identify figures as those of an adult or a child according to the size of the figure and its position in the picture. One of the pictures is shown in Figure 1.24.

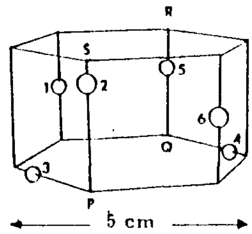
Figure 1.24. A diagram used by Jahoda and McGurk (Jahoda and McGurk, 1974a, p. 261.)

1.3.2. Tests involving students' use of depth cues

Sets of questions have been developed and made use of which concentrate on testing students' understanding of depth cues, on the assumption that the task of visualisation depends on the understanding of these cues (Seddon, Tariq and Dos Santos Veiga, 1984).

Nicholson and Seddon (1977a, 1977b), El Farra (1982) and Seddon, Adeola, El Farra and Oyediji (1984) used diagrams which require the student to identify a particular spatial relationship within a cuboid or hexagonal framework, using the depth cues of foreshortening of lines, overlap, relative size and tone. Students' responses were used to deduce whether the diagram was being interpreted in terms of two or three dimensions. Most students displayed a certain level of three-dimensional interpretation. Examples of the questions used are given in Figure 1.25.

HEXAGONAL FRAMEWORK



Horizontal displacements

a. Which ball, 1 or 3, is nearer to the vertical plane PQRS?

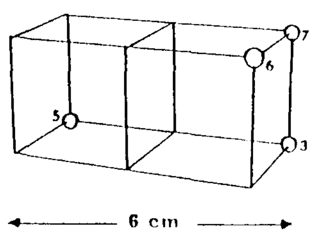
b. Which ball, 4 or 6, is nearer to the vertical plane PQRS?

Vertical displacements

a. Which ball, 2 or 5, is higher on the framework?

b. Which ball, 2 or 6, is at the same height on the framework as ball 1?

CUBOID FRAMEWORK



Diagonal displacements

a: Which ball, 3 or 6, is nearer to ball 5?

b. Which ball, 6 or 7, is further from ball 5?

Figure 1.25. Examples of questions in Nicholson and Seddon's test (Nicholson and Seddon, 1977a, p. 386.)

Evans and Seddon (1978) tested the response of students to four depth cues: relative size, foreshortening of lines, distortion of angles and overlap. Students were asked to study a three-dimensional model from a particular viewpoint and to choose which one of four diagrams correctly represented the model. The configuration of one cue in the diagrams was varied while the rest remained constant. Examples of their diagrams are shown in Figure 1.26. Students understood distortion of angles and overlap cues better than the cues of relative size and foreshortening of lines.

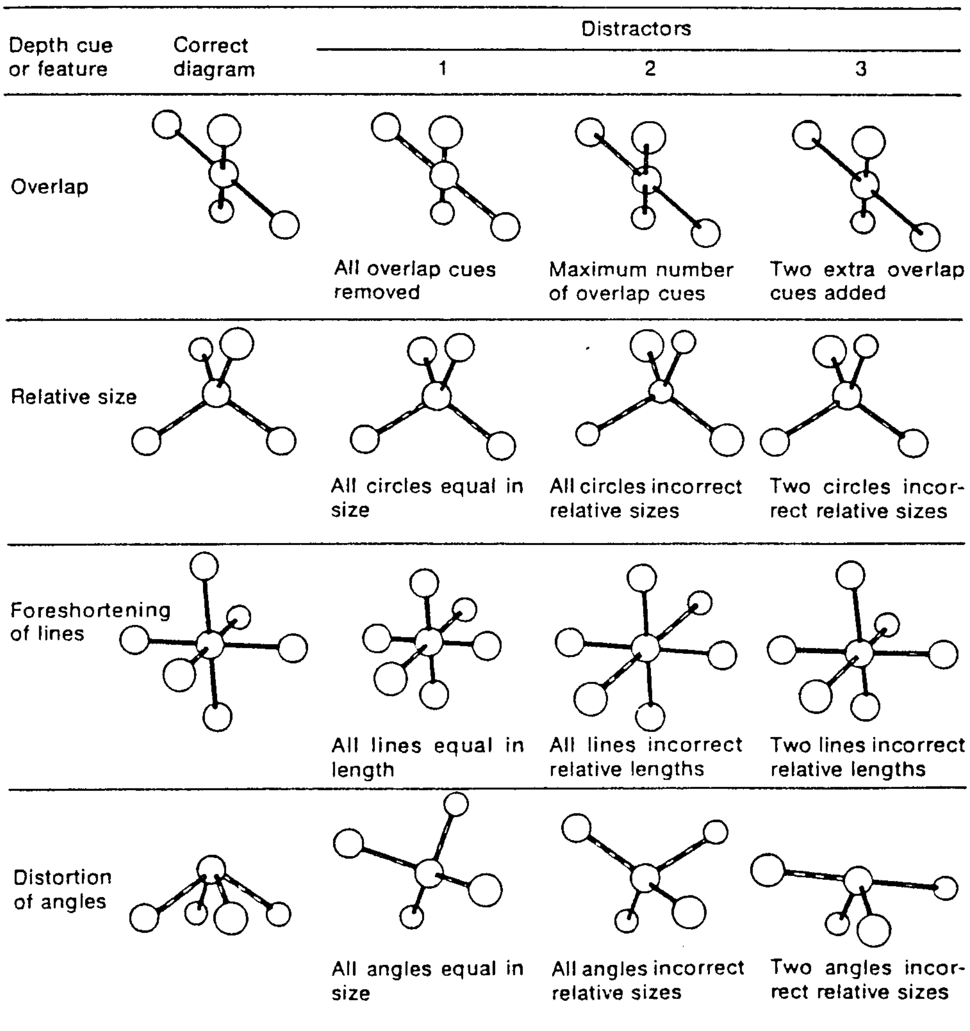


Figure 1.26. Example of diagrams on the cues test (Evans and Seddon, 1978, p. 315.)

1.3.3. Tests on students' ability to relate models to diagrams

Nicholson and Seddon (1977a) built framework models which were placed in viewing boxes to give a particular viewpoint. Students looked at four diagrams and chose the one that correctly represented a particular model. In a variation of this test, students looked at a diagram and chose which one of four models on display was correctly represented by the diagram. They also constructed models from diagrams (Seddon and Nicholson, 1985). A viewing box used for displaying the models is shown in Figure 1.27.

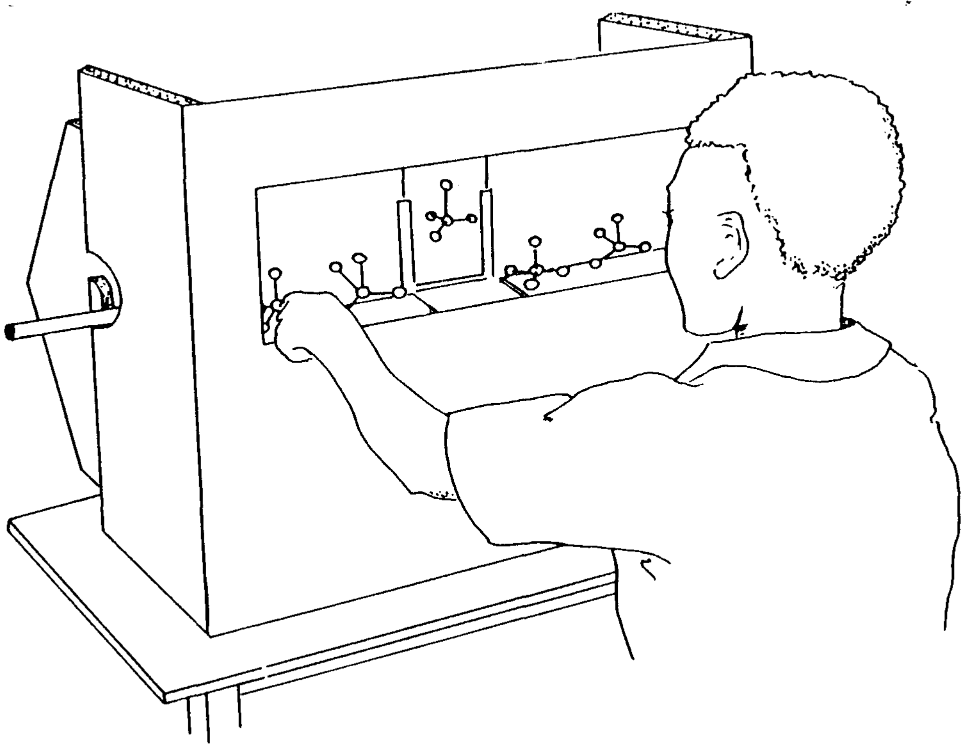


Figure 1.27. A viewing box used to display models (Seddon and Nicholson, 1985, p. 61.)

1.3.4. Tests on students' ability to visualise operations on diagrams

One of the first tests involving the visualisation of the effect of a spatial operation was developed by Shepard and Metzler (1971), who used pairs of perspective line drawings of ten solid cubes attached face to face to form a rigid armlike structure with three right-angled "elbows" as illustrated in Figure 1.28 below.

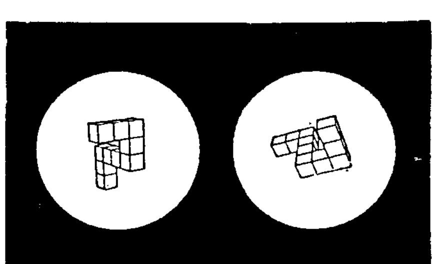


Figure 1.28. An example of drawings used by Shepard and Metzler (Shepard and Metzler, 1971, p. 702.)

Subjects had to rotate the drawings to discover whether the two drawings depicted objects of the same three-dimensional shape or not. Subjects' reaction time was found to increase linearly with the angular difference in the portrayed orientation, but was no longer for a rotation in depth than for a rotation in the picture plane. The results of Tapley and Bryden (1977) agreed with these findings.

Seddon and his co-workers (Seddon, Tariq and Dos Santos Veiga, 1982; Seddon, Adeola, El Farra and Oyediji, 1984; Seddon, Eniaiyeju and Jusoh, 1984; Seddon, Tariq and Dos Santos Veiga, 1984; Seddon and Shubber, 1984, 1985a, 1985b; Seddon, Eniaiyeju and Chia, 1985; Seddon and Eniaiyeju, 1986; Seddon and Moore, 1986a, 1986b) used multiple choice questions to test students' ability to visualise the effect of spatial operations. The questions involved diagrams of the structures that would be obtained after rotations about the X-, Y- and Z-axes, after reflections across the XY, XZ and YZ planes, and after inversions. Examples of the test items are illustrated in Figure 1.29 below. They used structures in which one central atom is directly connected to two, three, four, five or six other atoms. Only the regular spatial configurations found in real molecules were used. The diagrams were drawn by a computer using a programme developed by Cole and Adamson (1969); they are accurate in terms of perspective.

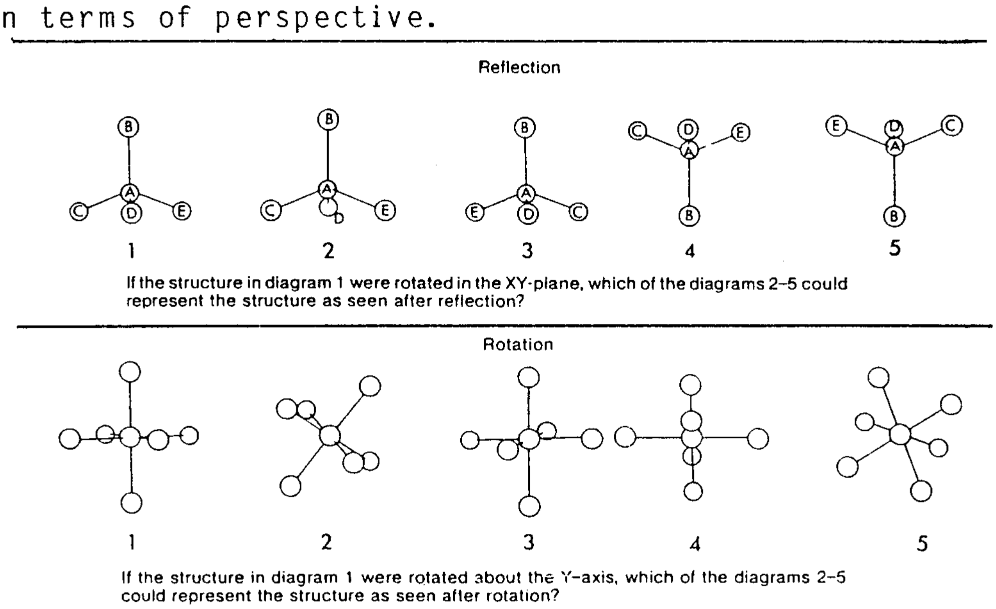


Figure 1.29. Examples of items testing reflection and rotation (Seddon, El Farra and Jusoh, 1984, p. 192.)

Rochford (1987a, 1987b) developed a test on the visualisation of pictorial molecular structures to measure the following skills:

i) skill in perceiving depth and distance in pictures and photographs of simple molecules;

ii) skill in matching diagrams of simple molecules rotated in three dimensions;

iii) skill in visualising the relative positions of ions in diagrams of crystal lattices;

iv) skill in matching diagrams of scale models of molecules with their ball and stick counterparts; and

v) skill in identifying diagrams of three-dimensional frameworks presented from a variety of perspectives.

Examples of his items are given in Figure 1.30 below.

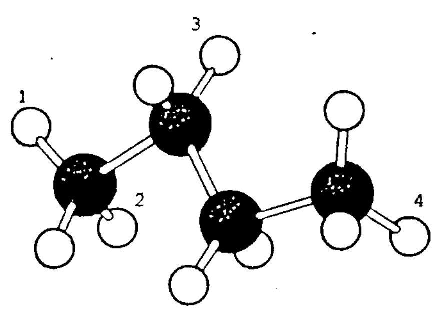
Q.3 The diagram on the right is a ball-and-stick representation of a molecule of n-butane C_4H_{10}. The hydrogen atom which is furthest from your eyes, i.e. which is furthest back in the diagram is hydrogen atom number

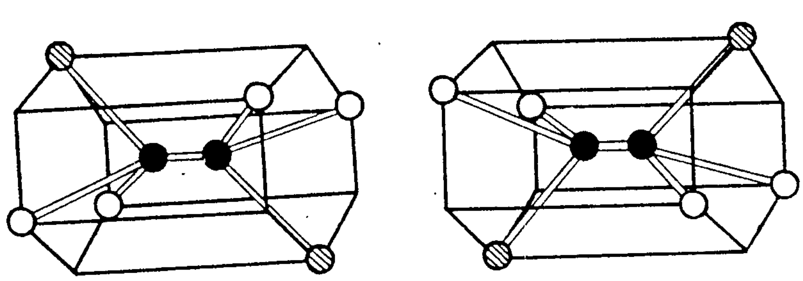
1

2

3

4





W

Z

30. Molecule W is the same as molecule Z rotated through

1. 30°
2. 60°
3. 90°
4. 180°

Figure 1.30. Examples of test items used by Rochford (Rochford, no date, pp. 4, 19.)

1.3.5. Correlation between three-dimensional visualisation and achievement in chemistry

Talley (1973), Baker and Talley (1974) and Small and Morton (1983) used spatial visualisation tests of the type published by Ekstrom, French, Harmon and Derman (1976), such as the "planes through solids" test, in conjunction with tests of chemistry content. Significant positive correlation between spatial visualisation and achievement in chemistry was found. Students with adequate three-dimensional visualisation skills tend to achieve significantly better than visually inept students in many scientific subjects, including chemistry (Blade and Watson, 1955; Siemankowski and MacKnight, 1971; Baker and Talley, 1974; Just, 1979; Taylor, 1980, 1983; Hyman, 1982; Dixon, 1985; Millroy and Rochford, 1985; Pribyl and Bodner, 1985; Rochford, 1985; Carter, La Russa and Bodner, 1987; Rochford, 1987a; Keen, Fredman and Rochford, 1988; Rochford and Sass, 1988). Rochford (1987a, 1987b) used the results of his Visualization of Pictorial Molecular Structures test to predict students' success in chemistry. Talley (1973) claims that students with greater experience in visualisation obtain significantly better scores for the higher level abilities in Bloom's taxonomy (Bloom, 1956), and are better critical thinkers. It has also been suggested that students may fail chemistry due to poor visualisation skills, rather than due to a lack of intelligence or motivation (Baker and Talley, 1972).

Three-dimensional visualisation may be useful for predicting final academic performance; and as a diagnostic tool for identifying students in need of remedial assistance (Rochford and Sass, 1988).

1.4. Review of the literature on the rectification of problems associated with three-dimensional visualisation

Although some researchers (Thurstone, 1950; Smith, 1964; Witkin, 1969; McFie, 1973) believe that visualisation skills cannot be taught, but that the capacity is innate, there are enough positive studies to indicate that it can be enhanced through carefully constructed learning sessions (Blade and Watson, 1955; Brinkmann, 1966; Saunderson, 1973; DeBono, 1976; Lord, 1985; Rochford, 1987b).

Early attempts to devise remedial teaching methods in tasks involving three-dimensional visualisation were mainly concerned with primary school children and with adults with little or no formal education (Dawson, 1967; Forge, 1970; Davies, 1973; Duncan, Gourlay and Hudson, 1973; Deregowski, 1974; Leach, 1975). When it was later recognised that students in chemistry courses also have difficulty in this connection, remedial instruction to improve three-dimensional thinking in chemistry was developed. Rochford (1987b) suggested that specific intervention in spatial chemistry would be more effective than general spatial geometry programmes.

Instruction made use of various teaching aids. Models, shadows, stereodiagrams and series of diagrams on slides or overhead projector transparencies were used. Each method will be discussed in this section. Some methods focused on the improvement of the three-dimensional visualisation of structures, by helping to improve students' understanding of depth cues. Others aimed at improving students' visualisation of the various types of operations on diagrams of molecules and crystal structures.

1.4.1. Use of models and shadows

An important method for the improvement of students' ability in three-dimensional visualisation is by the teaching of depth cues. Four instructional programmes were developed by Oyediji (1978), each programme for explaining the use of one of the following four depth cues: overlap, foreshortening of lines, distortion of angles and relative size. Each programme provides written instructions on how the cue is to be used, and illustrates the cue's application in diagrams. The text refers to models of the diagrams. In the programmes concerned with relative size, distortion of angles and foreshortening of lines, the cues were demonstrated using shadows of the model projected by a light situated at the student's viewpoint. Thus the shadow has an outline which is identical to that of the diagram representing the model.

Models and shadows have also been made use of to improve students' visualisation of the effect of operations on diagrams. Seddon, Eniaiyeju and Jusoh, (1984) used three programmes to teach visualisation of the rotation operation. In the first, diagrams were given and the answers were supplied. In the second programme, the student was allowed to observe a model and rotate it, before answering the question. In the third programme the student was allowed to rotate a model and observe its shadow, before answering the question.

Nicholson and Seddon (1977a), El Farra (1982) and Seddon, Adeola, El Farra and Oyediji (1984) used a programme aimed at enhancing three-dimensional visualisation of relationships within cuboid and hexagonal frameworks. In this programme the student views a model of the framework before answering a question relating to a diagram of the model.

1.4.2. Use of stereodiagrams

Stereodiagrams are a useful tool for teaching three-dimensional representation. In this technique a pair of drawings or photographs are produced, one showing how an object would appear when viewed by the right eye, the other showing the left eye view. A viewing device is then used to view the pair of diagrams simultaneously in such a way that the right eye sees only the right eye view and the left eye sees only the left eye view. An illusion of a three-dimensional object results. An example of a pair of stereodiagrams is shown in Figure 1.31 below.

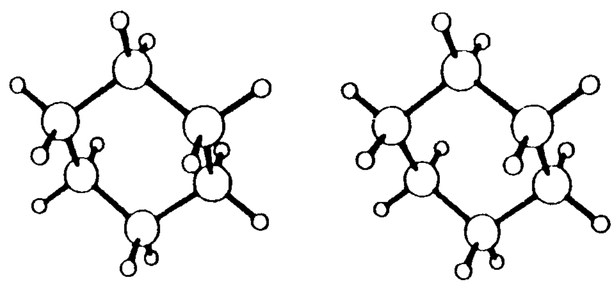


Figure 1.31. Example of a pair of stereodiagrams
(a) left eye view (b) right eye view
(Johnstone, Letton and Speakman, 1980, p. 172.)

The use of stereodiagrams has been recommended by Chang (1976), Gelbard (1976) and Hayman (1977); and Jensen (1982) suggests that stereodiagrams be used as an alternative to models, as they save cost, storage space and time. They are also found to motivate students by their novelty. The relative spatial positions of the atoms, either in a molecule or in the unit cell of a crystal, can be seen clearly using stereodiagrams (Johnstone et al, 1980). Stereodiagrams may help to bridge the gap between models and diagrams in the teaching of stereochemistry. Students who respond correctly to stereodiagrams generally transfer this ability to normal diagrams (Rozelle and Rosenfeld, 1985).

1.4.3. Use of a series of diagrams

Another teaching method used by Seddon and his co-workers (Seddon, El Farra and Jusoh, 1984; Seddon, Eniaiyeju and Jusoh, 1984; Seddon, Tariq and Dos Santos Veiga, 1984; Seddon and Shubber, 1984, 1985a, 1985b; Seddon and Moore, 1986a) employs a series of diagrams showing successive steps in the rotation of a molecule. The diagrams can be projected on slides or on overhead projector transparencies. The method has also been applied to reflection, showing theoretical steps in the reflection of a molecule. Examples of the diagrams are illustrated in Figure 1.32 below.

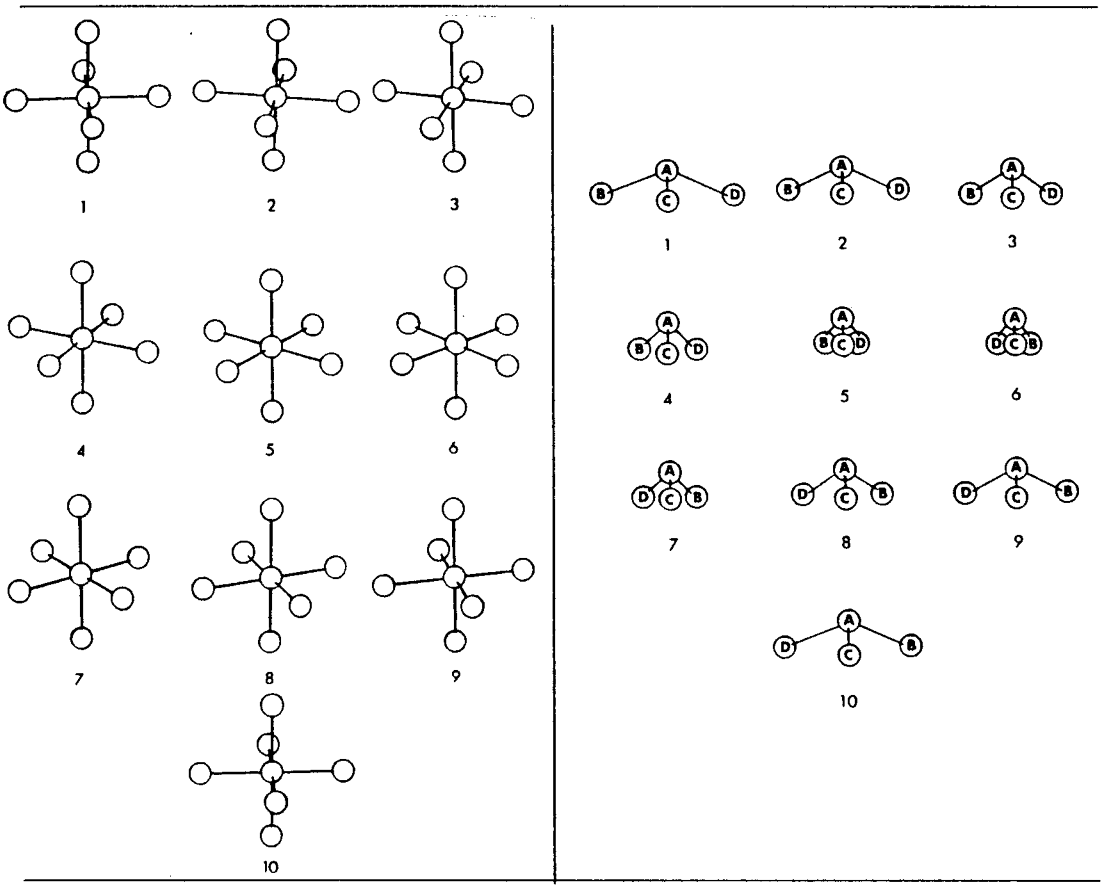


Figure 1.32. Examples of sequences of diagrams
(a) rotation (b) reflection
(Seddon, El Farra and Jusoh, 1984, p. 193)

1.4.4. Effectiveness of instruction programmes

According to Oyediji (1978), each of his programmes for teaching three-dimensional visualisation cues (see page 29) was found to be effective for that cue, but it did not lead to an improvement in other cues. He also found that instruction in one cue alone led to an improvement in three-dimensional visualisation; simultaneous instruction on two cues was, however, very much better (Seddon, Adeola, El Farra and Oyediji, 1984; Seddon and Shubber, 1985a).

All three programmes used by Seddon, Eniaiyeju and Jusoh (1984) (see page 30) to teach the visualisation of rotation, were found by them to be effective. They claim that the second programme, involving models as well as diagrams, was more effective than the first. This seems to indicate that seeing a rotating model helps students recognise how depth cues change during rotation. The third programme, employing shadows, was found to be even more effective; seeing depth cues changing in a shadow therefore appears to be significantly better than just watching the model rotate.

Stereodiagrams have been shown to lead to a significant improvement in students' ability to build three-dimensional models (Deregowski, 1974). Nicholson, Seddon and Worsnop, (1977) reported that stereoscopic diagrams were superior to conventional diagrams in teaching three-dimensional visualisation.

Seddon and co-workers (see page 31) found their programmes involving series of diagrams were most effective when the angle of rotation between successive diagrams was about 10°. Seddon and Moore (1986a) found that the use of a series of diagrams on their own was effective but, unexpectedly, the use of diagrams in conjunction with models was not. A possible reason for this discrepancy may be that students were unable to watch the models and the diagrams at the same time. According to Seddon, Tariq and Dos Santos Veiga (1984), programmes using a series of diagrams were effective for all axes and planes, but there was no transfer of learning between different axes and planes; they suggest that to be effective in improving students' visualisation of rotation and reflection as a whole, therefore, each axis and plane should be taught.

The instructional functions of colour in media presentations have also been investigated. Chute (1979) found that appropriate employment of colour promoted learning. This correlates with the results of Seddon and Shubber (1984), who found that their programmes (see page 31), which involved diagrams showing successive stages in the rotation or reflection of a molecule, were only effective if the diagrams were coloured.

1.5. Review of literature on the factors contributing to students' difficulties associated with three-dimensional learning

The tests and remedial instruction programmes described in Sections 1.3 and 1.4 have been made use of for various types of students. Tests have investigated differences between children of different ages, people of different educational levels, students from different cultural groups, and from different sexes.

Each of these factors will now be considered.

1.5.1. Cultural factors

Some researchers (Kidd, 1904; Herskovitz, 1959; Segall, Campbell and Herskovitz, 1966) have claimed that people from certain cultures have difficulty in identifying objects in pictures until the objects are pointed out to them. Three-dimensional visualisation by blacks, with various levels of education, has been tested in some detail (Hudson, 1960, 1962a, 1962b; Mundy-Castle and Nelson, 1962; Vernon, 1965a, 1965b; Mundy-Castle, 1966; Deregowski, 1968, 1971; Deregowski and Blyth, 1970; Duncan et al, 1973; Nicholson and Seddon, 1977a, 1977b). Although most subjects were able to identify the objects in the pictures, they generally seemed to visualise them on a two-dimensional basis. These results could be due to a lack of training and experience with pictures (Hudson, 1960, 1962a; Mundy-Castle, 1966; Kilbride and Robbins, 1968; Kilbride et al, 1968; Seddon and Nicholson, 1985). Subjects' recognition of photographs when first exposed to them has however been reported by Hochberg and Brooks (1962).

There could be a linguistic explanation for the difficulties mentioned above. Not all cultures perceive space in the same way, and languages often express ideas of depth differently (Littlejohn, 1963; Du Toit, 1966). This could be a serious problem in Hudson's test, which relies heavily upon verbal understanding. In his review of cross-cultural research in three-dimensional visualisation, Miller (1973, p. 148) concludes that "one cannot safely assume that members of different cultural groups are going to respond to pictorial materials in the same fashion." Other researchers (Page, 1970; Duncan et al, 1973; Jahoda and McGurk, 1974b; Leach, 1975) have not found that blacks have poor three-dimensional visualisation ability. Jahoda and McGurk (1974b, p. 265), using their test described in Section 1.3.1. (see page 21) conclude that although African children have some difficulty with depth perception, "the proposition that the majority of [them] fail to respond to depth cues in pictures has been clearly disconfirmed." Page (1970, p. 45) agrees with Doob (1965) that "Africans perceive drawings . . . no differently from anyone else."

Jahoda and McGurk (1974a, 1974b) and Cohen (1985) have worked with African, Chinese, European, American and American Indian children. They found that all children develop visualisation skills at approximately the same rate, regardless of culture.

Seddon and co-workers (Seddon et al, 1982; Seddon, Eniaiyeju and Jusoh, 1984; Seddon, Tariq and Dos Santos Veiga, 1984; Seddon and Shubber, 1984, 1985a, 1985b) tested students' ability to visualise spatial operations on diagrams representing molecules. They tested students from England, Portugal, Bahrain, Pakistan, Cape Verde and Nigeria. The visualisation ability of students from all these cultures was generally unsatisfactory.

1.5.2. Sexual factors

In addition to cultural differences, it has been postulated (Maccoby and Jacklin, 1974; Tapley and Bryden, 1977) that there are consistent sex differences in three-dimensional visualisation ability, although some researchers disagree (Brinkmann, 1966; Staver and Halsted, 1985; Golbeck, 1986; Liben and Golbeck, 1986).

Seddon and Nicholson (1985) report that there are sex differences in the understanding of diagrams of molecules in Nigerian children, but not in English children. They suggest that English boys and girls are given equal opportunity in learning to understand diagrams, whereas Nigerian boys have more opportunities than girls. They found that boys in both cultures were better at constructing models from diagrams, perhaps indicating that boys' toys give more practice in manual dexterity than girls' toys.

Golbeck (1986) and Liben and Golbeck (1986) tested men's and women's perception of horizontality and verticality. They found that although men performed better than women on physical tasks, this was not the case on non-physical tasks. Golbeck (1986) suggests that this could be because, although women have the underlying spatial competence, they are less likely to use it effectively, since they lack adequate knowledge of the relevant physical phenomenon. Sex differences in visualisation may therefore be sociological and not innate.

1.5.3. Age and education

Hudson (1960) and Deregowski (1968) tested the ability of children of various ages, and of adults, to interpret pictures three-dimensionally. They both found that three-dimensional visualisation depends on experience with the conventions used in diagrams, rather than on age or formal education. Thus primary and secondary school children and teachers were three dimensional perceivers, while illiterate adults were two dimensional perceivers, as were African miners and domestic servants, who, although educated, had little experience with pictures.

The ability to interpret pictures three-dimensionally has been tested for children from three to ten years old (Wilcox and Teghtsoonian, 1971; Benson and Yonas, 1973; Jahoda and McGurk, 1974b). It was found that visualisation improved with age, reaching near perfection in ten year olds. In a contradictory study, however, Seddon and Nicholson (1985) reported no improvement with age among six to ten year olds.

1.6. Conclusion

Richardson (1972) suggests that the formation and control of neural images is one of the most critical aspects of higher cognitive function. Researchers have found that over half the adult population in the United States of America have difficulty manipulating and controlling images (Maccoby and Jacklin, 1974; McGee, 1979). Hilton (1986) believes that students' spatial visualisation skills have in fact declined over the last twenty years. The problem may be even more severe in developing countries, where students are reported (Miller, 1973; Walker, 1979; Petterson, 1982; Seddon and Shubber, 1984) to have difficulty in even the simpler problem of recognition of spatial relationships; let alone visualisation of the effects of a transformation on the spatial relationships.

CHAPTER 2

OUTLINE OF THE PRESENT RESEARCH

2.1. Introduction

Chemistry is the science that deals with "the composition, structure and properties of substances, and of the transformations they undergo" (Penguin English Dictionary, 1985). Chemical substances are composed of three-dimensional particles; every molecule, atom and orbital has a three-dimensional structure. When an orbital, atom, molecule, or crystal lattice is represented in two dimensions on paper, the ability to visualise the structure three-dimensionally is needed in order to understand the representation. Thus three-dimensional visualisation is a central skill in chemistry.

In order for students to understand those concepts in chemistry that require three-dimensional visualisation, they must first develop the skills required for three-dimensional visualisation. Chemistry teaching mainly concentrates on the facts, concepts and principles of chemistry, and enough time is not often devoted to the development of the skills necessary for the student to cope with these facts, concepts and principles (Lord, 1985).

As already pointed out in chapter 1, there is strong evidence that many chemistry students have difficulty with three-dimensional visualisation. Models are generally used by teachers to illustrate the structures of crystals and molecules, and also the effect of spatial operations on these structures.

Most textbooks advise students to use models; for example Fessenden and Fessenden (1982, p. 110) state that "it is often difficult to visualise a three-dimensional molecule from a two-dimensional illustration. Therefore . . . we strongly urge you to use a set of molecular models."

Models are beneficial in teaching; they aid students' understanding of concepts that require three-dimensional visualisation. It is, however, essential for students, as learning progresses, to be able to visualise structures and spatial operations without the use of physical models; otherwise they will be seriously handicapped when they read textbooks and journals which have to rely mainly on two-dimensional representations. It seems imperative, therefore, that time should be spent helping students to develop adequate visualisation skills.

In Chapter 1 a review was given of previous research on various aspects of three-dimensional visualisation. In this chapter the research undertaken for this thesis is outlined. The objectives, scope, method and plan of this research will be discussed.

2.2. Objectives of this research

As indicated in Chapter 1, there have been several previous investigations into students' difficulties in three-dimensional thinking. These studies have generally aimed to identify the nature and extent of students' difficulties. This was also an aim of the present research. In addition, however, this research aimed to identify reasons for the students' difficulties.

The main objectives of this research were thus to:

a) identify those aspects of three-dimensional thinking that cause difficulty for second year chemistry students at the University of Bophuthatswana (Unibo);
b) identify the reasons for these difficulties;

c) devise and administer a remedial programme of instruction to help to overcome these difficulties;
d) test the effectiveness of the remedial programme by the analysis of the results of pretests and post-tests.

Previous studies of sex differences in visualisation ability, discussed in Section 1.5.2 (page 35), showed no consensus among the researchers. A subsidiary aim of this research was to test whether, within a group of students at the University of Bophuthatswana, there was a difference in three-dimensional visualisation ability between men and women.

2.3. Scope of the project

The various aspects of three-dimensional thinking required in chemistry were considered in Chapter 1 (Section 1.2.2, page 5). Of these, the simplest and most widely used operations are rotation and reflection, and this research was restricted to a detailed study of these two aspects only.

The various types of representation of three-dimensional structures were outlined in Section 1.2.3 (page 13). Two of these were chosen for this research: ball and stick formulae (Section 1.2.3.1) and dimensional formulae (Section 1.2.3.2). These are the two most widely used methods of representing simple molecules on paper.

In Section 1.2.3 the cues which are made use of in a ball and stick formula were discussed. They are: overlap, foreshortening of lines, distortion of angles, relative size and tone cues. This research was restricted to a consideration of only the first three of these cues. These three cues are widely used in the literature. Although the cue of relative size has been used in several previous studies (Oyediji, 1978; Seddon, El Farra and Jusoh, 1984; Seddon Eniaiyeju and Jusoh, 1984; Seddon, Tariq and Dos Santos Veiga, 1984; Seddon et al, 1985; Seddon and Nicholson, 1985; Seddon and Shubber, 1985a; Seddon and Eniaiyeju, 1986;

Seddon and Moore, 1986a, 1986b), it was decided to ignore this cue, in this study, for the following reasons:

a) The effect would be relatively small because of the short distances involved in the model of a molecule, and hence would be difficult for a student to detect. Typical differences in the diameter of circles in the diagrams drawn in the tests would be 0,5 mm, or less than 10%.

b) The atoms of different elements have different sizes. Hence it may confuse a student, who may not know whether a circle of bigger size represents an atom which is closer to us, or an atom with a larger radius.

c) Although this cue may be useful for portraying depth, it is not used throughout the literature. Standard texts which do <u>not</u> use this cue include Fessenden and Fessenden (1982), Solomons (1982), Norman and Waddington (1983); Atkins (1986) and Morrison and Boyd (1987). When complicated molecules are represented the relative size cue would become complex and confusing.

In the dimensional formula representation of a molecule, wedges, , and diminishing dashes, , are used as cues. A bond coming out of the plane of the paper towards the viewer is always represented by a wedge; or . For a bond going into the plane of the paper, away from the viewer, different notations have, however, been used by different authors. It has been represented by ------ (Basolo and Johnson, 1964; Cram and Cram, 1978; Moore and Barton, 1982; Norman and Waddington, 1983), or (Fessenden and Fessenden, 1982; Solomons, 1982; Gillespie <u>et al</u>, 1986), or (Masterton, Slowinski and Stanitski, 1985; Atkins, 1986).

The notation was used in this study as it gives the impression of a line receding and is very different from the representation of a bond in the opposite direction, , thus minimising the possibility of confusion.

This research therefore made use of five depth cues altogether: overlap, foreshortening of lines, distortion of angles, wedges and dashes.

Before discussing the research method and the design of this research, a review of the methods used in educational research will be given.

2.4. Review of methods made use of in educational research

2.4.1. Introduction

In this section, methods of educational research are reviewed. Many research methods are descriptive; they account for what has already occurred. These methods include historical research, developmental research, surveys, case studies, correlational research and role playing. On the other hand, in experimental research, the researcher arranges for events to happen. A brief description of each research method follows, together with reasons for the choice of methods in the present research.

2.4.2. Historical research

Historical research involves "the systematic and objective location, evaluation and synthesis of evidence in order to establish facts and draw conclusions about past events." (Cohen and Manion, 1985, p. 48) It seeks to reconstruct the past and to apply it to the present and the future. This method is not relevant for the present study.

2.4.3. Developmental research

Developmental research describes present relationships among variables in a given situation and accounts for changes occurring in those relationships as a function of time (Cohen and Manion, 1985). An example is the qualitative changes occurring in children's thinking as outlined by Piaget (1971).

This method is not relevant for the present study, as the students' visualisation ability at a particular level of education is being investigated, rather than students' development over time.

2.4.4. Surveys

A survey gathers data at a particular time. It either describes the nature of existing conditions or determines relationships between specific events (Cohen and Manion, 1985). It makes no attempt to change the existing situation. The survey can take the form of a written questionnaire, an oral interview or a test of attainment or performance. Since the interview obtains verbal responses, it allows opportunity for greater depth than a written questionnaire, but it is also more prone to subjectivity. Tests such as the ones made use of in this research are examples of surveys.

2.4.5. Case studies

Case studies are interpretive and subjective. The characteristics of an individual unit such as a child, a class or a school are observed. The aim of a case study is to analyse the unit with a view to establishing generalisations about the wider population to which the unit belongs (Cohen and Manion, 1985).

2.4.6. Correlational research

Correlational research is concerned with understanding phenomena or behavioural patterns by studying the relationships between variables. For example, teacher effectiveness may depend on factors such as intelligence and motivation. It is also used to predict outcomes when relationships between variables are known (Cohen and Manion, 1985). It is used here in the analysis of the results obtained to investigate relationships between three-dimensional visualisation as a whole, and its component aspects.

2.4.7. Action research

Action research involves a "small-scale intervention in the functioning of the real world and a close examination of the effects of such intervention" (Cohen and Manion, 1985, p. 208). It takes place in a specific context. Researchers and practitioners work together and take part in implementing the research. It is self-evaluative, and aims to improve practice in some way.

2.4.8. Role playing

Role playing involves participation in simulated social situations that are intended to give information about real life social episodes. This method is useful for social studies, rather than cognitive ones.

2.4.9. Experimental research

In experimental research, the investigator deliberately controls and manipulates the conditions which determine events. He or she makes a change in the value of the independent variable and observes the effect of that change on the dependent variable (Cohen and Manion, 1985).

The independent variable is "that factor which is measured, manipulated or selected by the experimenter to determine its relationship to an observed phenomenon" (Tuckman, 1972, p. 37). It is often a stimulus of some kind such as an instruction programme. The dependent variable is that factor which is observed and measured to determine the effect of the independent variable. It is a response, such as competence in some task after instruction.

Experimental research includes pre-experimental, quasi-experimental and true experimental designs, and ex post facto research. Each of these will be discussed.

2.4.9.1. Symbols used in research designs

Before discussing the designs, an explanation of the symbols used to represent the designs is needed. The system of symbols described below is generally used in research designs:

> X represents the exposure of a group to an experimental variable, the effects of which are to be measured, while Y represents the exposure of a group to a treatment which is irrelevant to the experimental variable being measured. A blank space represents a control or the absence of a treatment. 0 designates an observation or measurement. R indicates random assignment to treatment groups, whereas dashed lines indicate intact groups. X's and 0's in the same row are applied to the same subjects, and X's and 0's vertical to one another are simultaneous. Left to right order indicates temporal sequence (Campbell and Stanley, 1963; Tuckman, 1972; Cohen and Manion, 1985).

2.4.9.2. Pre-experimental designs

A pre-experimental design is represented in Figure 2.1. It involves one group, and there is a pretest and a post-test. An observation, 0_1, is made, an experimental manipulation, X, is then introduced, and the variable is remeasured, 0_2. Observed differences may, however, be due to other factors, rather than the experimental variable.

experimental	0_1	X	0_2

Figure 2.1. A pre-experimental design

2.4.9.3. True experimental designs

True experimental design involves a pretest and a post-test with an experimental group and a control group. A control group is "a group of subjects whose selection and experiences are identical in every way possible to the treatment or experimental group except that they do not receive the treatment" (Tuckman, 1972, p. 72). Two groups are constituted by randomisation, as indicated by the symbol R. The blank space indicates a control or absence of treatment. The subjects are randomly assigned to either the experimental or the control group. This controls independent variables, and is particularly effective in large samples. Extraneous factors should influence both groups equally. An example of an experimental design is given in Figure 2.2.

experimental	R	O_1	X	O_2
control	R	O_3		O_4

Figure 2.2. A true experimental design

A problem with the above design may be the interaction effect of testing; for instance the pretest may sensitise subjects to the experimental variable. For this reason two more groups can be added who do not experience the pretest, as represented in Figure 2.3.

experimental	R	O_1	X	O_2
control	R	O_3		O_4
experimental			X	O_5
control				O_6

Figure 2.3. A true experimental design which controls for pretest sensitisation

Since the present research involves a skill, rather than an attitude, pretest sensitisation should not be a serious factor.

2.4.9.4. Quasi-experimental designs

Quasi-experimental design involves a non-equivalent control group, as shown in Figure 2.4.

experimental	0_1	X	0_2
control	0_3		0_4

Figure 2.4. A quasi-experimental design

The dashed line denotes that the experimental and control groups have not been equated by randomisation and are non-equivalent. Groups should be composed from the same population and should be as alike as possible.

2.4.10. Ex post facto research

This is retrospective research. It investigates cause and effect relationships by observing an existing condition and searching back in time for possible causal factors. There are two kinds of design in ex post facto research; co-relational research and criterion group research.

The design of co-relational research is represented in Figure 2.5 below. X designates a variable or treatment, and 0 refers to an observation or measurement (Campbell and Stanley, 1963; Tuckman, 1972; Cohen and Manion, 1985). The variable X could cause the observed phenomenon, 0.

X	0

Figure 2.5. A co-relational design

Criterion group research is represented in Figure 2.6. In this type of research, two sets of subjects are observed, one of which has the attribute O, the other of which does not. The variable X that causes only one group to have the attribute is discovered.

	O_1
X	-----
	O_2

Figure 2.6. A criterion group design

A weakness in ex post facto research is the lack of control over the independent variable. It cannot be manipulated or randomised.

2.4.11. <u>Validity of experiments</u>

The validity of an experiment may be defined as the extent to which it measures what it is intended to measure. It is important to ensure both internal and external validity in an experiment. An experiment has internal validity if the outcome of the experiment is a function of the experimental treatments rather than the result of other causes not dealt with in the experiment. There is external validity if the results obtained would apply in the real world to other similar programmes (Tuckman, 1972).

Threats to validity are more severe for quasi-experiments than for true experiments. Several possible threats to internal validity will now be considered.

a) <u>History</u>
   Events other than experimental treatments occur during the time between the pretest and the post-test. These events may produce effects that could be attributed to differences in treatment.

b) <u>Maturation</u>
   Subjects change between any two observations. These changes could produce differences that are independent of the experimental treatments.

c) Statistical regression

There is a tendency in post-test measurements for scores to regress towards the mean. The scores of higher scorers tend to decrease while those of lower scorers increase. This is because chance factors are more likely to contribute to extreme scores than to average scores, and such chance factors are unlikely to reappear during a second testing.

d) Testing

Pretests can sensitise subjects to the purposes of the experiment, and provide practice which leads to higher scores in post-test measures.

e) Experimental mortality

Some subjects may drop out during the course of the experiment. Although the groups were randomly selected initially, the residue may be different from the group that began.

Threats to external validity are factors which limit the degree to which generalisations can be made.

a) Failure to describe independent variables explicitly

Independent variables must be adequately described, so that replications of experimental conditions are possible.

b) Lack of representativeness of available and target populations

The subjects participating in the experiment may not represent the same population as those to whom the researcher wishes to generalise the findings.

c) The Hawthorne effect

Subjects involved in the experiment may perform better than those who are not involved due to psychological effects. The fact that they are involved may make them more eager to perform well. To minimise the Hawthorne effect, the control group should not be ignored while the experimental treatment is taking place, but should be given a treatment which is irrelevant to the experiment.

The design of an experiment with a Hawthorne effect control group is represented in Figure 2.7. below.

experimental	R	0_1	X	0_2
control	R	0_3	Y	0_4

Figure 2.7. An experimental design with a Hawthorne effect control group

2.5. Design of this research

This research made use of a true experimental design. The subjects were randomly divided into two groups, an experimental group and a control group. The control group experienced an irrelevant intervention, in order to minimise the Hawthorne effect. The experimental design is represented in Figure 2.8 below.

experimental	R	0_1	X	0_2
control	R	0_3	Y	0_4

Figure 2.8. Design of this research

where R indicates that random assignment of the students was made to the experimental and control groups,

0 refers to the measurement of three-dimensional visualisation ability, by tests which will be described in chapter 3,

X represents the exposure of the experimental group of students to a treatment (instruction in three-dimensional visualisation), the effects of which are to be measured, Y represents the exposure of the control group to a treatment which is irrelevant to the experimental variable being measured,

X's and O's in the same row are applied to the same students,

X's and O's vertical to one another are simultaneous; O_1 and O_3 therefore refer to pretests and O_2 and O_4 refer to post-tests,

Left to right order indicates temporal sequence,

Parallel rows represent groups equated by randomisation.

2.6. The plan and details of the research

In Section 2.2 (page 39) the objectives of this research were stated. In this section the plan of study adopted, so as to achieve the stated objectives, is described.

This research study could be divided into three main stages:

a) the design and administration to students of pretests and the analysis of their answers. The main objectives of this stage are to identify the nature, extent and particularly the reasons for students' difficulty with aspects of three-dimensional thinking involving rotation and reflection;

b) the design and administration of remedial instruction with a view to helping students overcome their difficulties (identified in stage (a));

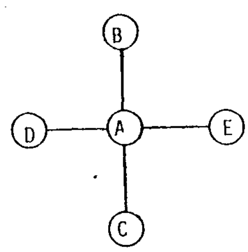
c) The assessment of the effectiveness of the remedial instruction programme, by the analysis of the answers to the pretest and the post-test.

Each of these three stages will now be discussed in greater detail.

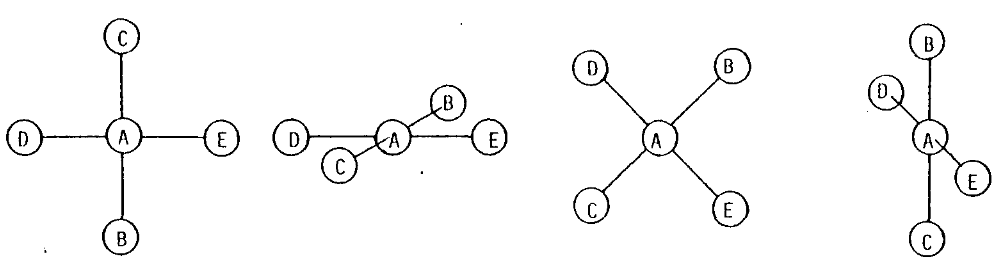
a) As already indicated, this research has been restricted to rotation and reflection. Rotation is possible around each of the three Cartesian axes, X, Y and Z, and reflection can take place in each of the planes, XY, XZ and YZ. Test items were designed to test all these aspects.

Two types of questions were designed; the question paper was therefore divided into two sections. One type, which was given in Part A of the question paper, was meant to test the overall ability of a student to answer correctly a question on rotation or reflection. An example of such a question is:

Consider the square planar molecule represented in diagram 1 below:

1 

Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Y-axis?



2 3 4 5

To answer this type of question, which may be called a standard question, competence in many aspects and steps is required. To answer the question given above logically, for example, it is necessary to do the following:

i) understand the meaning of some of the special words and phrases that are used;
ii) visualise the three-dimensional structure of the molecule using the depth cues;

iii) visualise the orientation of the Y-axis;
iv) visualise the positions of the atoms after rotation;
v) link the above aspects (i - iv) into a logical sequence.

Lack of competence in any one of the component steps given above would result in failure. With the type of questions given in Part A (which is the type which has mainly been used by previous researchers in this field) it is not possible to identify the reasons for students' difficulty. One can only describe the overall competence of the student. To identify the reasons for failure, therefore, questions were designed to test students' competence in each of the component steps required to answer a standard question. These questions were given in Part B of the question paper.

To summarise: the questions in Part A of the question paper are meant to test students' overall three-dimensional visualisation ability while the questions in Part B are meant to reveal the reasons for their difficulties. By comparing a student's answers to questions in Part A and Part B it may also be possible to identify whether his/her difficulties are associated with the strategy that must be used for linking the component steps into a logical sequence.

b) From the results of Part B the component steps causing difficulty in Part A were identified. Instruction on each of these steps was designed; this also included exercises for the students to work through. The instruction focused on four main areas:

i) the understanding of the meaning of special words and phrases (e.g. rotation about the X-axis) used in the questions;
ii) the use of the depth cues, particularly the overlap cue, to help in the visualisation of the three-dimensional structures of the molecules;
iii) the recognition of the orientation of the various axes and planes;

iv) the identification of the positions of the atoms after an operation of rotation or reflection had been performed upon the molecules

This instruction programme was administered to the experimental group, while the control group received instruction on the various types of skills required for dealing with relationships between variables.

c) After the instruction, both groups were retested in order to ascertain whether the instruction programme had been effective in improving students' three-dimensional visualisation skills. The post-test was similar in its design and objectives to the pretest. As in the pretest there were two parts to the question paper. These were Part A and Part B.

The essential elements of the research therefore were: the pretest - Part A and Part B, remedial instruction, and the post-test - Part A and Part B.

The tests will be described in Chapter 3 and the remedial instruction programme in Chapter 5.

2.7. Subjects for the research

The subjects were second year undergraduate chemistry students, enrolled for a four-year Bachelor of Science (Education) degree at the University of Bophuthatswana. Bophuthatswana is the so-called "homeland" of the Tswana, given "independence" by South Africa in 1977. None of the students tested spoke English as a first language. English is, however, the medium of instruction at the university, and all students are generally presumed to be proficient in English.

Chemical concepts requiring three-dimensional thinking, such as stereochemistry and the shapes of molecules (Section 1.2.2, page 5) are introduced in the first year of study. Thus the second year students had already been exposed to some aspects of three-dimensional thinking.

Thirty-one students were tested, twenty men and eleven women.

2.8. Administration of the tests

The pretests were administered on 21 April 1988. No time limit was set for the tests. All students finished the Part A questions within forty minutes. After a twenty minute break for refreshments, Part B questions were administered. Students needed from forty to eighty minutes to finish Part B.

Remedial instruction was administered on 16 September 1988. It took the form of a ninety-minute session from 8.00 - 9.30 a.m., with a five minute break in the middle of the session.

Post-tests were administered one week after instruction, on 23 September 1988. Students needed up to forty-five minutes for Part A and from forty to sixty minutes for Part B. There was a twenty minute break for refreshments between the two parts of the test.

CHAPTER 3

DESIGN OF THE TEST ITEMS FOR THE PRETEST AND THE POST-TEST

3.1. Introduction

In Chapter 2, the plan of the research study was outlined: the study involved a pretest administered at the start, and a post-test given after remedial instruction. Both pretest and post-test consisted of Part A questions, which tested students' overall ability to solve a three-dimensional problem associated with the operations of rotation and reflection, and Part B questions, which tested the students' competence in the component steps required for the solution of the test items given in Part A.

In this chapter the test items are discussed. An explanation is provided of how the diagrams given in the test items were drawn, and how the various questions in Parts A and B were designed. The questions in Part B, which test students' competence in the component steps required to answer the Part A questions, were designed by an analysis of the answers to the questions in Part A. The reliability and the validity of the tests are also discussed. The test items are discussed here in general terms. The specific test items made use of and their objectives will be given and discussed later (in Chapter 4).

Appendix 1 shows the Part A and Part B question papers, for both the pretest and the post-test. The test items in the Part A paper are arranged in random order, as they were given to the students.

3.2. Design of the test items

In Sections 3.2 - 3.4, the design of the test items in the pretest will be considered. This is followed, in Section 3.5, by an explanation of the differences between the pretest and the post-test.

3.2.1. Molecular structures used in the test items

Molecules having six structures were used in the tests: T-shaped, trigonal planar, square planar, tetrahedral, trigonal bipyramidal and octahedral. Each of these structures is found in real molecules. Some examples are indicated below:

T-shaped	ClF_3, ICl_3
trigonal planar	BF_3, CO_3^{2-}
square planar	XeF_4, ICl_4^-
tetrahedral	CH_4, NH_4^+
trigonal bipyramidal	PF_5, $SnCl_5^-$
octahedral	SF_6, PCl_6^-

It can be seen that three planar and three non-planar structures were used.

The number of test items both in Part A and in Part B of the paper that involve a given structure is indicated below:

	Part A	Part B
T-shaped	3	7
trigonal planar	3	6
square planar	3	9
tetrahedral	5	4
trigonal bipyramidal	5	4
octahedral	5	2

Arbitrary structures were used in question 1 (see page 145).

3.2.2. How the diagrams were drawn

Two types of representations were made use of in the test items to represent molecules: ball and stick formulae and dimensional formulae.

The diagrams were drawn by hand, using a 0,35 mm Rotring 2000 isograph pen and a Faber Castell map-making stencil No 958 N. Circles drawn were 6 mm in diameter. Lines for representing a bond in the plane of the paper were drawn 12 mm long, while bonds not in the plane of the paper were foreshortened.

In each molecule the central atom is bonded to between three and six atoms. The letters A, B, C, D, E, F and G were used to label the atoms. Only spatial configurations found in real molecules were used, except in Part B, question 1 (page 145) where hypothetical molecules were used. The bond lengths in the hypothetical molecules were not all equal. This was done to isolate the overlap cue, without the presence of foreshortening of lines and distortion of angles. The letters used to label the atoms were not rotated or reflected with the diagrams: thus the student visualised the effect of the operation on the structure of the molecule only, not on the labels. This is consistent with what is done in most chemistry textbooks.

The molecules were presented in the form in which students encounter them in textbooks (e.g. Solomons, 1982; Norman and Waddington, 1983; Morrison and Boyd, 1987).

3.3. Design of the test items in the Part A section of the question paper

3.3.1. Introduction

The test items in Part A of the question paper test students' competence in three-dimensional thinking associated with rotation and reflection. There were twenty-four questions and these are given in Appendix 1 (pages 131 - 143). Twelve of these involved rotation; four questions for each of the three Cartesian axes (X, Y and Z). For each axis, two questions involved molecules represented by ball and stick formulae, and the other two used molecules represented by dimensional formulae.

There were twelve questions concerning reflection; four of these concern each of the Cartesian planes, XY, XZ and YZ. For each plane, two questions involved molecules represented by ball and stick formulae, while the other two questions made use of molecules represented by dimensional formulae.

3.3.2. How the responses were designed for Part A

(a) Questions involving rotation

The questions are of the multiple choice type. In each question the distractors and the correct answer were arranged in random order, using a table of random numbers (Weinberg and Goldberg, 1979).

Each question involved four responses. The responses were designed in a logical and consistent manner. Three responses corresponded to the result that would be obtained when rotation takes place about each of the Cartesian axes, X, Y and Z. The last response corresponded to reflection in the YZ plane for questions concerning the X-axis (pages 134, 141 and 143), reflection in the XZ plane for questions concerning the Y-axis, (pages 132, 136, 138 and 140) and reflection in the XY, XZ or YZ plane for questions concerning the Z-axis (pages 133, 137, 139 and 142). The XY plane was not used for the reflection of a planar molecule, as it would yield a structure identical to the original molecule (question 4, page 133 and question 12, page 137).

The angles through which the molecules represented in the stem of the multiple choice questions were rotated to obtain the responses were from 45° to 180°; the value selected was one which gave clear, unambiguous diagrams. The angles and the direction of rotation were not specified in the question, because the correct answer could be obtained by visualising rotation in either direction (clockwise or anticlockwise).

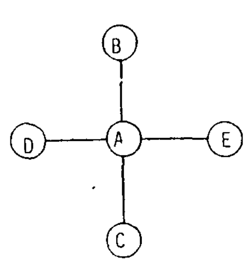
(b) Questions involving reflection

In each question there were four responses. Three of these were obtained by reflecting the structure in each of the three Cartesian planes, XY, XZ and YZ. The last response was obtained by rotating the molecule through 180° about one of the axes.

3.4. <u>Design of the test items in the Part B section of the question paper</u>

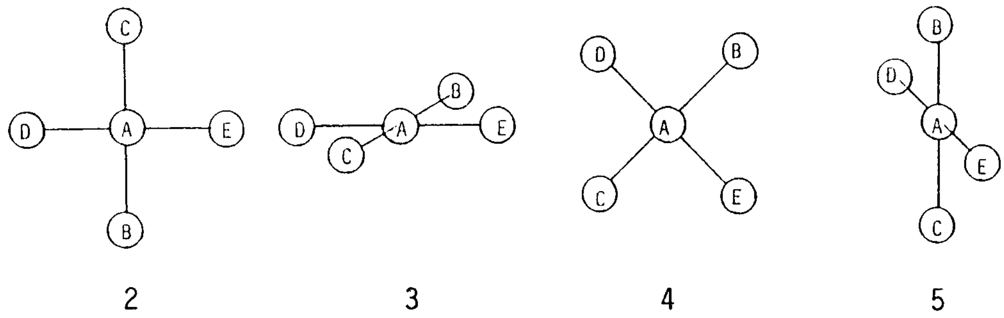
In Part B, the test items were designed to test each of the component steps required for the solutions of the standard three-dimensional problems given in Part A. Before Part B questions could be devised, it was necessary, therefore, to identify these component steps. In order to do this, the solution to each question in Part A was first analysed into its component steps. To illustrate, consider question 1, (page 132), which is reproduced below.

1. Consider the square planar molecule represented in diagram 1 below:



1

Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Y-axis?



The main steps involved in the solution of this problem are indicated below:

1. The first step is the three-dimensional visualisation of the molecule represented in diagram 1.

   For this one must use any depth cues given to determine whether the molecule is planar or non-planar. If it is non-planar, one must then determine
   a) which atoms are in the plane of the paper,
   b) which atoms are closer to the viewer than the plane of the paper,
   c) which atoms are further away from the viewer than the plane of the paper.

   In diagram 1 there is no overlap. All the bond lengths are equal, and all the angles are of the correct size (90°). Therefore all the atoms are in the plane of the paper.

2. The second main step is the visualisation of how the depth cues and the positions of the atoms would change after the operation of "rotation about the Y-axis".

   For this one must identify the Y-axis and recognise that, in the molecule considered, line BAC lies along the Y-axis. One must also understand the meaning of the phrase "rotation about the Y-axis" and understand that rotation involves the concept of turning.

After rotation about the Y-axis, atoms A, B and C would not change position, but atoms D and E would move out of the plane of the paper. D would be further away from the viewer than the plane of the paper, and E would be closer than the plane of the paper, or vice versa. The depth cues involving atoms D and E would change. Atom A would overlap atom D, and atom E would overlap atom A, or vice versa. Lines AD and AE would be foreshortened, and angles involving atoms D and E would be distorted.

3. The final step is the identification of which one of the given responses is consistent with the description in step 2. In this question, diagram 5 is the correct answer.

Similar steps are involved in the answering of all the items given in Part A of the question paper.

Since the main objective of Part B questions is to identify the reasons for students' failure, each Part B question was designed to test, whenever possible, just one component step, or one piece of knowledge, required for the solution of a Part A question.

Table 3.1 lists each of the component steps required for the solution to question 1, together with a set of test items to test these steps. The table shows that nine test items are required to identify all possible reasons for failure in the Part A question considered.

Table 3.1

Test items that were designed to test each component step involved in the solution of Question 1

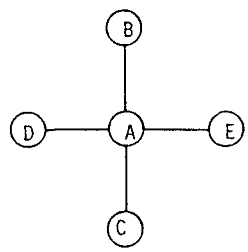
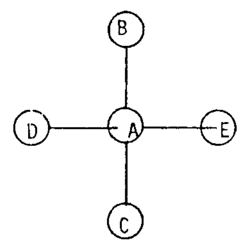
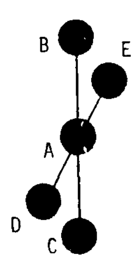
Component step	Test item
1. Three-dimensional visualisation of the molecule represented in question 1 (page 60) using the overlap cue only.	1. Consider the hypothetical molecules represented below:   1 2 i) In which of these molecules are all the atoms in the plane of the paper? ii) Which of the atoms are closer to you than the plane of the paper? iii) Which of the atoms are further away from you than the plane of the paper?
2. Three-dimensional visualisation of the molecule represented in question 1 (page 60) using foreshortening of lines and distortion of angles.	2. Consider the symmetrical square planar molecule represented below:  Which (if any) of the atoms B, C, D and E are not in the plane of the paper?

Table 3.1 (continued)

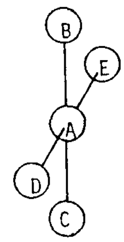
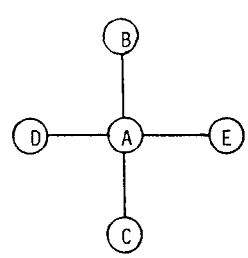
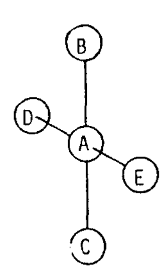
Component step	Test item
3. Three-dimensional visualisation of the molecule represented in question 1 (page 60) using all three depth cues (overlap, foreshortening of lines and distortion of angles).	3. Consider the molecule represented below:  i) Which (if any) of the atoms B, C, D and E are not in the plane of the paper? ii) Which (if any) of the atoms are closer to you than the plane of the paper? iii) Which (if any) of the atoms are further away from you than the plane of the paper.
4. Identification of the Y-axis.	4. Consider the square planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper: 1  About which axis (X, Y or Z) must the molecule be rotated if it is to look like diagram 2? 2 

Table 3.1 (continued)

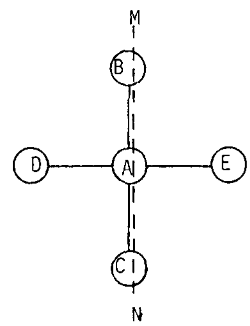
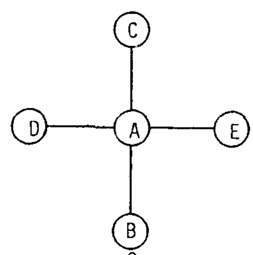
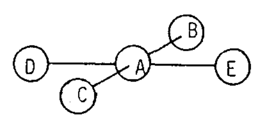
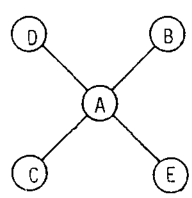
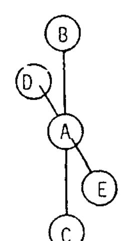
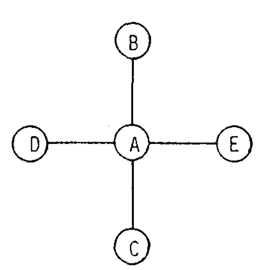
Component step	Test item
5. Understanding of the meaning of the phrase "rotation about the Y-axis". (Answers to this test item were analysed in conjunction with the answers to question 1 (page 60). This is explained on page 95.)	5. Consider the square planar molecule represented in diagram 1 below: 1  Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if you turned it around the axis corresponding to the dashed line MN?  2  3  4  5
6. Visualisation of the positions of atoms after the operation of rotation about the Y-axis.	6. Consider the square planar molecule represented below in which all the atoms are in the plane of the paper:  Which (if any) of the atoms A, B, C, D and E might not be in the plane of the paper if the molecule were rotated about the Y-axis?

Table 3.1 (continued)

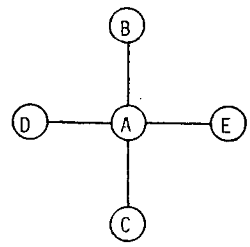
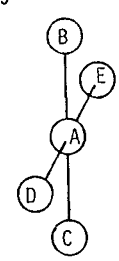
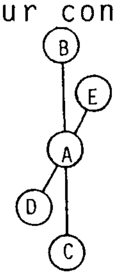
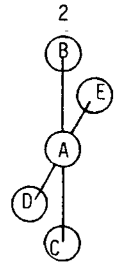
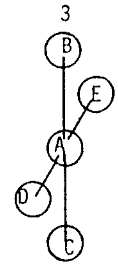
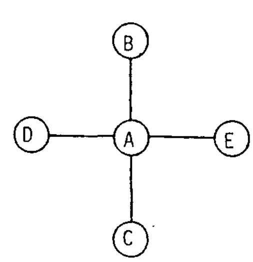
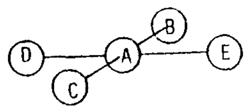
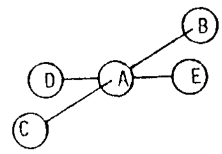
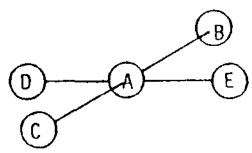
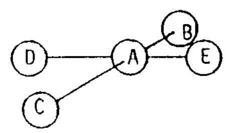
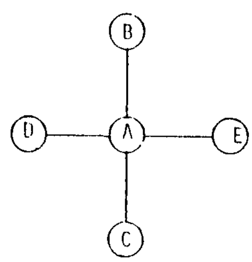
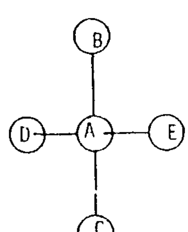
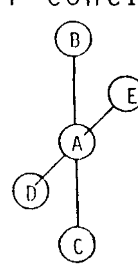
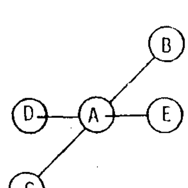
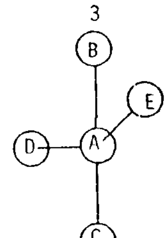
Component step	Test item
7. Visualisation of the overlap cue after the operation of rotation about the Y-axis.	7. Consider the square planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper: 1  Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the Y-axis? State briefly how you came to your conclusion?  2  3  4  5
8. Visualisation of fore-shortening of lines after the operation of rotation about the Y-axis.	8. Consider the square planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper: 1 

Table 3.1 (continued)

Component step	Test item
8. (continued)	Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the Y-axis? State briefly how you came to your conclusion.  2  3  4  5
9. Visualisation of distortion of angles after the operation of rotation about the Y-axis.	9. Consider the square planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper: 1  Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the Y-axis? State briefly how you came to your conclusion.  2  3  4  5

Analysis shows that many of the component steps are essentially common to many of the Part A questions, and hence the number of questions that had to be designed for Part B was not large: fourteen questions were sufficient. More than this number of questions were however used so as to check reliability.

How the Part B questions were designed by the analysis of a Part A question (question 1) was illustrated in Table 3.1. A similar analysis was done for the other Part A questions, and other Part B questions were designed. From this large pool of Part B questions, a set was selected that was sufficient to test students' competence in all the component steps required for the solution of three-dimensional problems involving rotation and reflection. Planar molecules and ball and stick formulae were used, whenever possible, in order to keep the questions simple. The Part B test items are given in Appendix 1 (pages 144 - 161).

The results of the analysis of Part A questions are indicated in Table 3.2 which summarises the component steps required for the solution of Part A questions and also links each question in Part B to the corresponding Part A question. The component steps are listed in the first column of Table 3.2. Part A questions where this step is involved are listed in the second column and the Part B questions that test competence in this step are given in the third column. For example, the visualisation of a molecule using the overlap cue is needed to solve questions 1, 2, 6, 8, 10, 12, 13, 17, 18, 19, 20 and 22 in Part A. Question 1 in the Part B question paper tests this step.

3.5. Differences between pretest and post-test questions

The Part A and Part B questions were of the same form in both the pretest and the post-test. Different molecular structures were, however, used in the pretest and the post-test.

Table 3.2

Connection between Part A and Part B test items

Component step needed to solve a Part A question	Part A questions that need this step	Part B questions that test this step
Three-dimensional visualisation of a molecule using the overlap cue	1, 2, 6, 8, 10, 12, 13, 17, 18, 19, 20, 22	1
Visualisation of a molecule using foreshortening of lines and distortion of angles	1, 2, 6, 8, 10, 12, 13, 17, 18, 19, 20, 22	2, 3
Visualisation of a molecule using all three cues (overlap, foreshortening of lines and distortion of angles)	13, 17, 18, 19, 20, 22	4, 5
Visualisation of a molecule using wedge and dash cues	3, 4, 5, 7, 9, 11, 14, 15, 16, 21, 23, 24	6, 7
Understanding of the meaning of the phrase "rotation about the X-axis"	5, 6, 19, 23	8
Understanding of the meaning of the phrase "rotation about the Y-axis	1, 9, 14, 17	9
Understanding of the meaning of the phrase "rotation about the Z-axis"	4, 12, 15, 22	10
Identification of the X-axis	5, 6, 19, 23	12
Identification of the Y-axis	1, 9, 14, 17	11
Identification of the Z-axis	4, 12, 15, 22	13
Visualisation of the positions of atoms after an operation of rotation about the X-axis	5, 6, 19, 23	14
Visualisation of the positions of atoms after an operation of rotation about the Y-axis	1, 9, 14, 17	15
Visualisation of the positions of atoms after an operation of rotation about the Z-axis	4, 12, 15, 22	16

Table 3.2 (continued)

Component step needed to solve a Part A question	Part A questions that need this step	Part B questions that test this step
Visualisation of the representation of the overlap cue after an operation of rotation about the X-axis	6, 19	17
Visualisation of the representation of the overlap cue after an operation of rotation about the Y-axis	1, 17	18
Visualisation of the representation of foreshortening of lines after an operation of rotation about the X-axis	6, 19	19
Visualisation of the representation of foreshortening of lines after an operation of rotation about the Y-axis	1, 17	20
Visualisation of the representation of distortion of angles after an operation of rotation about the X-axis	6, 19	21
Visualisation of the representation of distortion of angles after an operation of rotation about the Y-axis	1, 17	22
Visualisation of the representation of the wedge and dash cues after an operation of rotation about the X-axis	5, 23	23
Visualisation of the representation of the wedge and dash cues after an operation of rotation about the Y-axis	9, 14	24
Understanding of the meaning of the phrase "reflection in the XY plane"	2, 7, 16, 20	25
Understanding of the meaning of the phrase "reflection in the XZ plane"	3, 10, 18, 24	26
Understanding of the meaning of the phrase "reflection in the YZ plane"	8, 11, 13, 21	27

Table 3.2 (continued)

Component step needed to solve a Part A question	Part A questions that need this step	Part B questions that test this step
Identification of the XY plane	2, 7, 16, 20	28
Identification of the XZ plane	3, 10, 18, 24	30
Identification of the YZ plane	8, 11, 13, 21	29
Visualisation of the position of the atoms after reflection in the XY plane	2, 7, 16, 20	31
Visualisation of the position of the atoms after reflection in the XZ plane	3, 10, 18, 24	32
Visualisation of the position of the atoms after reflection in the YZ plane	8, 11, 13, 21	33

3.6. Reliability and validity of the tests

3.6.1. Reliability

The reliability of a test is "a measure of its consistency in measuring whatever it purports to measure" (Bell, 1978, p. 427). Reliability can be measured in a number of ways.

One way of checking reliability is the test-retest method. The test is given to a set of students. A short time later, the same test, or an alternative form of the test, is given to the same students. A correlation coefficient, whose value can range from -1,0 to +1,0, is computed between the two sets of test scores. If the correlation coefficient is near +1,0 the test is reliable. This approach to reliability involves the determination of test consistency over time. It is also possible to determine the internal consistency of a test by the split-half method. The test is divided into two halves. Odd and even numbered questions can form the two halves, or the items can be divided into matched pairs. These matched pairs of items are randomly divided into two groups. Scores on the two halves are computed and correlated. Since each of the two halves is shorter than the full test, the resultant correlation is corrected to that expected for a full-length test. The correction is done using the Spearman-Brown correction formula (Slavin, 1984, p. 211):

$$r_c = \frac{n\, r_a}{1 + (n-1)r_a}$$

where r_c is the corrected reliability estimate

r_a is the correlation coefficient for the short forms of the test

n is the number of parts into which the test has been split.

For split-halves $n = 2$ and therefore $r_c = \dfrac{2\, r_a}{1 + r_a}$.

Another measure of reliability is the Kuder-Richardson formula, KR-20 (Slavin, 1984, p. 208). It is used to calculate reliability when there are only two possible responses to each question, such as right and wrong, on a test assumed to measure one variable. The extent to which the test items are all measuring this same characteristic can be determined by the KR-20 formula. Reliability can be calculated using the formula

$$\text{KR-20} = \left(\frac{I}{I - 1}\right)\left(1 - \frac{\bar{x} - \dfrac{\Sigma c^2}{N^2}}{s_x^{\,2}}\right)$$

where I = the number of items on the test

$\bar{x}$ = the mean of the total scores

s_x^2 = the variance of the total scores

Σc^2 = the sum of the squares of the number of individuals who got each item correct

N^2 = the square of the number of scores.

The split-half measure of reliability will be used in the present studies. The reliability coefficient is calculated in Section 4.5.1 (page 84) and Section 6.3 (page 112) for the results of Part A of the pretest and the post-test respectively.

3.6.2. Validity

The validity of a test is "the extent to which the test measures what it is supposed to measure" (Bell, 1978, p. 427). There are two types of test validity: content validity and criterion (or concurrent) validity.

Content validity refers to the extent to which the test measures the content of the material it is intended to cover. The sample items in the test should be representative of the set from which the sample is drawn. The content in Part A questions involves rotation about the X-, Y- and Z-axes, and reflection in the XY, XZ and YZ planes. Content validity was ensured by designing several questions on each of these aspects.

Criterion validity refers to the extent to which the scores on the test agree with scores on other tests that measure the same thing. For an internal check on criterion validity of the tests in the present programme, each objective was tested with two test items. If the scores for the two questions agree, then the test could be considered valid. For example, questions 6 (page 134) and 19 (page 141) in Part A both aim to test visualisation of the rotation of a molecule represented by a ball and stick formula about the X-axis.

CHAPTER 4

RESULTS OF THE PRETESTS AND THEIR ANALYSIS

4.1. Introduction

In Chapter 3, the design of the tests was discussed. In this chapter the pretest results are first recorded. The results are then discussed and analysed statistically. Before considering the results, the statistical methods which were employed will first be discussed.

4.2. Choice of statistical tests

Various statistical methods of analysis are available, each being appropriate under a particular set of circumstances. Two important factors that must be considered when choosing a statistical method are the type of measurement scale used and whether the tests are parametric or non-parametric. These factors are discussed below.

4.2.1. Types of measurement scales

A measurement scale is "a set of rules for quantifying or assigning numerical scores to a particular variable" (Tuckman, 1972, p. 142). A measurement scale may be nominal, ordinal, interval or ratio.

4.2.2. Parametric and non-parametric tests

Certain assumptions must be satisfied by the data in order for parametric tests to be valid. The distribution must be normal, the variance must be homogeneous, and continuous equal interval measurements must be made.

(a) Normal distribution

The distribution must be symmetrical about its mean. This is illustrated in Figure 4.1 (a).

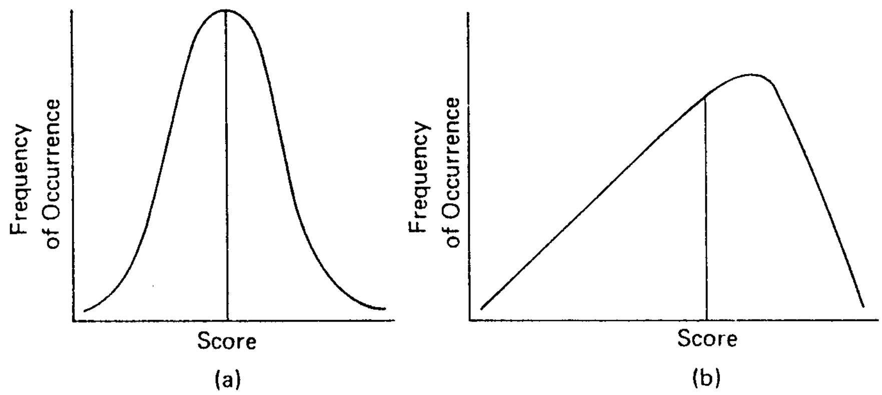


Figure 4.1. Examples of distribution curves
(a) normal (b) skewed (Tuckman, 1972, p. 227)

(b) Homogeneity of variance

The variance or spread within the groups must be approximately equal. For example, if the distribution shown in Figure 4.2 is obtained for two groups, a parametric test would be difficult to interpret.

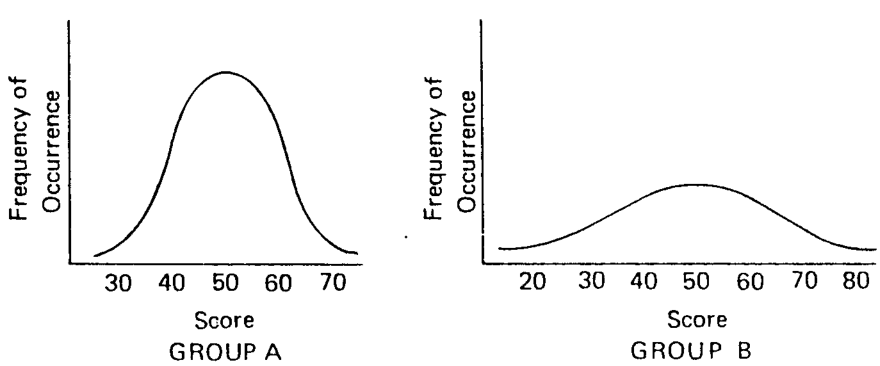


Figure 4.2. Examples of different variances
(Tuckman, 1972, p. 227)

(c) Continuous equal interval measures

The scores must represent an interval or ratio scale.

All these assumptions were satisfied in the test results in the present research (as will be shown in Section 4.5.2, page 85); therefore parametric tests were used.

Non-parametric tests do not require normal distribution or equal group variances. They are based on nominal or ordinal measurement.

4.3. Review of statistical methods

Statistics can be descriptive or inferential.

a) Descriptive statistics

Descriptive statistics describe a group of data. This description makes use of the concepts of central tendency and variability.

A widely used measure of central tendency is the mean, $\bar{x}$. It is computed by adding the scores (x_1, x_2, x_3 . . .) and then dividing by the number (N) of the scores.

$$\bar{x} = \frac{\Sigma x_i}{N}$$

One type of measure of the spread, or dispersion, of a distribution of scores is the standard deviation, s. It can be calculated using the following formula:

$$s = \sqrt{\frac{\Sigma(x_i - \bar{x})^2}{N - 1}}$$

The square of the standard deviation (s^2) is referred to as the variance of the scores.

b) Inferential statistics

Inferential statistics are used to compare groups of data to determine whether differences between them can be accounted for by chance fluctuations (Tuckman, 1972). Various statistical tests are widely used, and those that will be made use of in the analysis of the present research will now be reviewed.

(i) <u>The t-test for the comparison of the means from two independent groups</u>

This is a statistical test that allows comparison of two means ($\bar{x}_1$ and $\bar{x}_2$) to determine the probability that the difference between them is a real difference, rather than a chance difference. It can be calculated using the formula (Slavin, 1984, p. 177):

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}}$$

If the obtained t-value exceeds the critical t-value (for the appropriate degrees of freedom) at a specific probability level, then the null hypothesis (which states that the means being compared are equal) can be rejected at that probability level (Tuckman, 1972, p. 233). Probability levels normally used are 0,01 or 0,05 (Spiegel, 1972; Fridman, 1987).

(ii) <u>The t-test for the comparison of the means from two matched groups</u>

This is a variation of the t-test described in (i) above. It can be used either for the comparison of subjects from matched groups, or for the comparison of the scores (x_1 and x_2 of the same subjects under two different conditions or at two different times. It can be calculated using the formula (Slavin, 1984, p. 182):

$$t = \frac{\bar{D}}{\sqrt{\frac{s_D^2}{N}}}$$

where $\bar{D}$ = the mean of the difference scores, $x_1 - x_2$, for each subject

s_D^2 = the variance of the difference scores

N = the number of pairs of scores

(iii) Pearson Product-moment Correlation

The Pearson Product-moment correlation is used to deal with two interval variables (x and y), each of which is normally distributed. The correlation coefficient, r, gives an indication of the predictability of one variable given the other. The formula for a correlation coefficient, r, is (Slavin, 1984, p. 199):

$$r_{xy} = \frac{\Sigma xy - \frac{\Sigma x \Sigma y}{N}}{s_x s_y (N - 1)}$$

(iv) Analysis of Variance (ANOVA)

An analysis of variance (ANOVA) is an extension of the t-test and can be used for almost any number of independent variables. The simplest case is a comparison of three groups, where the effect of one independent variable on one dependent variable is analysed. This is called a one-way analysis of variance, or a K x 1 ANOVA, where K is the number of treatment groups. A comparison of three groups would thus be a 3 x 1 ANOVA. If equal or approximately equal sample sizes are used, the ANOVA is insensitive to violations of the normality and the homogeneity of variance assumptions.

A repeated measure analysis of variance is used when repeated measurements on the same subjects under a number of different conditions or treatments are taken (Fisher and McDonald, 1978; Ferguson, 1984). This is summarised in Table 4.1.

Table 4.1

Repeated measure analysis of variance

(Ferguson, 1984, p. 320)

source of variation	sum of squares	degrees of freedom	variance estimate
rows	SS_r	N_r-1	s_r^2
columns	SS_c	N_c-1	s_c^2
interaction	SS_{rc}	$(N_r-1)(N_c-1)$	s_{rc}^2
total	$SS_r+SS_c+SS_{rc}$		

where SS_r = sum of squares for subjects (rows)

SS_c = sum of squares for treatments (columns)

SS_{rc} = interaction sum of squares

N_r = number of subjects

N_c = number of treatments

s_r^2 = mean square for subjects

s_c^2 = mean square for treatments

s_{rc}^2 = interaction mean square

The F statistic for testing differences between treatments is given by $F_c = \dfrac{s_c^2}{s_{rc}^2}$.

(v) Analysis of Covariance (ANCOVA)

An analysis of covariance allows for differences in prior ability. It corrects for most of the student-to-student variation at the pretest stage. The pretest is used as the covariate. When covariates are highly correlated with the dependent variable, an analysis of covariance increases the statistical power. The analysis of covariance is summarised in Table 4.2.

Table 4.2
Analysis of covariance
(Slavin, 1984, p. 196)

source of variation	SS	df	MS	F
between groups	SS'_B	K-1	$MS'_B = \dfrac{SS'_B}{K-1}$	
within groups	SS'_W	N-K-1	$MS'_W = \dfrac{SS'_W}{N-K-1}$	$\dfrac{MS'_B}{MS'_W}$
Total	$SS'_B + SS'_W$	N-2		

where SS = sum of squares

df = degrees of freedom

MS = mean sum of squares

SS'_B = adjusted sum of squares between treatments

$= SS'_T - SS'_W$

SS'_W = adjusted sum of squares within treatments

$$= SS_W - \frac{\left(\Sigma xy - \dfrac{\Sigma x_1 \Sigma y_1}{N_1} - \dfrac{\Sigma x_2 \Sigma y_2}{N_2}\right)^2}{[(N_1-1)s_{x1}^2] + [(N_2-1)s_{x2}^2]}$$

SS_T = total sum of squares

$= SS_B + SS_W$

SS'_T = adjusted total sum of squares

$$= SS_T - \frac{\left(\Sigma xy - \dfrac{\Sigma x \Sigma y}{N}\right)^2}{\Sigma x_1^2 + \Sigma x_2^2 - \dfrac{(\Sigma x)^2}{N}}$$

K = number of treatments

N = number of subjects

MS'_B = adjusted mean square between groups

$$= \frac{SS'_B}{K-1}$$

MS'_W = adjusted mean square within groups

$$= \frac{SS'_W}{N-K-1}$$

(vi) Scheffé test

The ANOVA tells us whether the means from several groups are unequal, but does not tell us which means are different from each other. To investigate which of the means are not equal to each other, the Scheffé test can be used. It is a post-hoc multiple-comparison procedure for pairwise comparisons among means. It has as one of its assumptions that the F test of the ANOVA was found to be significant. It is applicable to samples of either equal or unequal size. The F statistic can be calculated for samples i and j using the formula (Weinberg and Goldberg, 1979, p. 364):

$$F = \frac{\left(\frac{\Sigma X_i}{N_i} - \frac{\Sigma X_j}{N_j}\right)^2}{MS_W\left(\frac{1}{N_i} + \frac{1}{N_j}\right)(K - 1)}$$

with K-1, N-K degrees of freedom.

4.4. Results of the pretest: Part A questions

As already indicated (page 52) the pretest question paper consisted of two parts: Part A and Part B. There were twenty-four Part A questions; twelve questions concerning rotation and twelve questions concerning reflection. There were thirty-three Part B questions. The question paper given to the students appears in Appendix 1. In this section the results for the Part A questions will be presented and analysed.

Table 4.3 shows the results for the Part A questions in the pretest. For each correct answer, 1 mark was awarded, and for an incorrect answer, 0 was given. The maximum possible score is 24, since there are 24 questions in Part A.

For convenience, each student is identified, in Table 4.3, by a number, from 1 to 31, and by his or her initials (see the first two columns in the table). The students in the experimental group are listed first, numbers 1 to 16; followed by those in the control group, numbers 17 to 31. The third column gives the sex of the student; M for a male student and F for a female student. Scores for each of the questions then follow.

The scores for questions involving the X-axis are given first, followed respectively by scores for the Y-axis, Z-axis, XY plane, XZ plane and YZ plane. For each axis or plane, the scores for questions involving ball and stick formulae are presented first, followed by the scores for questions involving dimensional formulae. In the table, B.S. denotes a molecule represented by a ball and stick formula, while D.F. stands for a molecule represented by a dimensional formula. As already mentioned earlier (page 56), the questions though designed in a logical sequence (in the sequence in which they are given in Table 4.3) were given in a random order in the question paper. The number of each question, as it appeared on the test paper, is also given. For example, in column 4, the heading "Q6, X-axis, B.S." means that this column contains the scores for question 6 (page 134) which involves rotation about the X-axis of a molecule represented by a ball and stick formula.

The last column indicates each student's total score; that is the total number of questions answered correctly by each student. The final row in the table shows the total number of students who had answered each question correctly. This is the sum of the scores in each column. For example, nine students answered question 6 (column 4) correctly. Subtotals for the experimental and control groups are also given.

As can be seen from Table 4.3, the results were generally poor. Only three students obtained a score greater than 50%. The highest score obtained was 15 out of 24 (63%) and the lowest score was 1 (4%). The results were particularly bad for those questions which involved the visualisation of reflection in the XY and XZ planes.

Table 4.3
Pretest results - Part A

Group	Number	Initials	Sex	Q6, X-axis, B.S.	Q19, X-axis, B.S.	Q5, X-axis, D.F.	Q23, X-axis, D.F.	Q1, Y-axis, B.S.	Q17, Y-axis, B.S.	Q9, Y-axis, D.F.	Q14, Y-axis, D.F.	Q12, Z-axis, B.S.	Q22, Z-axis, B.S.	Q4, Z-axis, D.F.	Q15, Z-axis, D.F.	Q2, XY plane, B.S.	Q20, XY plane, B.S.	Q7, XY plane, D.F.	Q16, XY plane, D.F.	Q10, XZ plane, B.S.	Q18, XZ plane, B.S.	Q3, XZ plane, D.F.	Q24, XZ plane, D.F.	Q8, YZ plane, B.S.	Q13, YZ plane, B.S.	Q11, YZ plane, D.F.	Q21, YZ plane, D.F.	Total score
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
experimental group	1	M.C.	M	0	0	1	0	0	0	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	5
	2	G.M.	M	0	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	4
	3	S.K.	F	0	0	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0	0	4
	4	B.R.	F	1	1	1	0	0	1	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	1	1	10
	5	N.M.	F	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	3
	6	I.M.	M	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	4
	7	D.D.	M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
	8	T.M.	F	1	1	0	0	1	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	1	1	0	0	8
	9	O.R.	M	0	0	1	0	1	1	1	0	1	0	1	1	0	1	0	0	0	0	0	0	1	1	0	1	11
	10	M.K.	M	1	1	1	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	11
	11	M.S.	M	1	0	1	0	0	1	0	1	1	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	8
	12	H.T.	M	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	1	0	0	1	5
	13	F.M.	F	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	1	0	4
	14	N.S.	F	0	1	1	1	1	1	0	1	0	1	1	0	1	0	1	0	0	0	0	0	0	1	1	1	13
	15	L.G.	M	1	0	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	1	6
	16	R.P.	M	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	4
	Subtotals			5	5	6	3	7	5	4	4	6	6	3	8	4	3	1	2	3	0	0	1	6	7	5	7	101
control group	17	L.S.	M	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0	1	0	0	0	1	5
	18	G.R.	M	0	0	1	0	1	0	0	0	1	1	1	1	0	0	0	0	0	0	0	1	0	1	1	1	10
	19	M.L.	M	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	1	0	0	1	0	0	0	5
	20	S.M.	M	0	0	1	1	1	0	0	1	0	1	0	0	1	1	1	0	1	0	1	0	1	0	0	0	11
	21	J.M.	M	0	0	1	1	0	1	1	1	1	0	0	0	1	0	0	1	1	0	0	0	1	1	1	1	13
	22	J.M.	F	0	0	0	0	1	0	0	0	0	1	1	0	0	1	0	0	0	0	0	1	1	1	0	0	7
	23	P.T.	F	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1	0	1	6
	24	A.M.	M	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	0	15
	25	L.M.	F	1	1	1	0	0	0	1	0	0	1	0	1	0	0	0	0	1	1	0	0	0	0	1	0	9
	26	M.M.	M	0	0	1	0	1	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	1	7
	27	M.K.	F	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
	28	L.M.	F	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	1	1	0	1	0	0	0	0	0	7
	29	T.M.	M	0	1	0	0	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	9
	30	B.M.	M	1	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	9
	31	A.M.	M	1	0	1	0	1	0	0	1	0	0	0	0	1	1	0	1	0	0	0	0	0	1	0	0	8
	Subtotals			4	3	7	3	8	4	8	6	5	10	6	7	4	3	1	4	5	3	3	4	7	6	4	6	123
	Total			9	8	13	6	15	9	12	10	12	16	9	15	8	6	2	6	8	3	3	5	13	13	9	13	224

Note on abbreviations: B.S. = ball and stick formula, D.F. = dimensional formula

4.5. Analysis of the results of the pretest for Part A questions

4.5.1. Reliability of the test

The split-half measure of reliability, as described in section 3.6.1 (page 71), was used. The test items were divided into matched pairs; the items in each pair tested the same objective. The test items in the two halves also had approximately the same number of planar and non-planar molecules. For example, question 6 and question 19 both tested visualisation of the rotation of a molecule represented by a ball and stick formula about the X-axis. Question 6 was assigned to one half, and question 19 to the other. Table 4.4 shows how the two halves of the pretest were constituted.

Table 4.4

Division of Part A test items into split-halves

	Test Item numbers
1st half	4, 6, 7, 10, 11, 12, 13, 14, 17, 20, 23, 24
2nd half	1, 2, 3, 5, 8, 9, 15, 16, 18, 19, 21, 22

Students' scores for the two halves were computed and correlated to obtain a reliability coefficient (r_C), using the formulae (see pages 72 and 78)

$$r_{xy} = \frac{\Sigma xy - \frac{\Sigma x \, \Sigma y}{N}}{s_x s_y (N - 1)}$$

$$r_C = \frac{2\, r_{xy}}{1 + r_{xy}}$$

It was found that $r_C = 0,69$ which is significant at the 0,01 level, indicating fair reliability. It is probable that some of the students answered the questions by random guessing. This would explain why the correlation was not higher.

4.5.2. Calculation of mean values and standard deviations

The results of Part A give an indication of students' competence in connection with three-dimensional thinking associated with the operations of rotation and reflection. From the results tabulated in Table 4.3, the mean values and the standard deviations were calculated, for the experimental and the control groups.

The maximum raw score possible is 24. Calculation showed that the mean score for the experimental group was 6,3 and for the control group it was 8,1. For both groups, the standard deviation was 3,4 and the variance, s^2, was 11,6. This information is summarised in Table 4.5.

Table 4.5

The Mean Scores ($\bar{x}$) and the standard deviation (s) of Part A results - Pretest

	Experimental group	Control group
N	16	15
$\bar{x}$	6,3	8,1
$\bar{x}$ (%)	26	34
s	3,4	3,4
s^2	11,6	11,6

From the above results it can be seen that the variances are homogeneous. This is a prerequisite for the use of parametric tests (see page 74).

4.5.3. Descriptive analysis of the results

Certain conclusions can be reached about subsets of questions in which students performed better than in others, from an inspection of the pretest results. Subsets which were investigated were ball and stick formulae and dimensional formulae; planar and non-planar molecules; rotation and reflection; rotation about the X-, Y- and Z-axes; and reflection in the XY, XZ and YZ planes. From the results, the following general trends are evident.

(a) There seemed to be no difference in students' ability to visualise operations performed on molecules represented by ball and stick formulae and dimensional formulae.

(b) Visualisation of operations was generally better with planar molecules than with non-planar molecules.

(c) The operation of rotation was generally visualised better than that of reflection.

(d) Visualisation of rotation about all three axes was achieved to much the same extent.

(e) Reflection in the YZ plane was visualised better than reflection in the other two planes. A possible explanation for this could be the way in which optics was taught in South African schools: students were taught that an image in a plane mirror is erect and is laterally inverted (Pienaar and Walters, 1980; Brink and Jones, 1975; Fourie, Kaske, Wessels and Van Huyssteen, 1985). This is true for the YZ plane, but is confusing for reflection in the other two planes. Fortunately the new syllabus has omitted this information (Pienaar, Walters, De Jager and Schreuder, 1985; Brink and Jones, 1988).

4.5.4. Percentages of students who failed questions concerning each axis or plane

Table 4.6 gives the percentages of students who failed Part A questions concerning the various axes and planes. A student was considered to have failed if less than 3 out of 4 questions were answered correctly. This pass mark (3 out of 4) was obtained by applying the binomial theorem to calculate the score which a random guesser would achieve with a probability of 5%.

Table 4.6

Percentages of students who failed questions concerning each axis or plane

axis or plane	experimental group	control group
X axis	81	80
Y axis	81	73
Z axis	94	67
XY plane	100	87
XZ plane	100	100
YZ plane	81	73

4.6. Results of the pretest, Part B questions

As explained in Section 3.4 (page 60), the Part B questions were designed to test the students' competence in each of the steps required for the solution of the Part A questions. The questions tested the following aspects:

(a) the three-dimensional visualisation of a molecule using the depth cues (questions 1 - 7 and 17 - 24);
(b) the understanding of the phrases "rotation about an axis (questions 8 - 10) and "reflection in a plane" (questions 25 - 27);
(c) the identification of the axes (questions 11 - 13) and planes (questions 28 - 30);
(d) the visualisation of the positions of the atoms after rotation (questions 14 - 16) and reflection (questions 31 - 33).

In the solution of a Part A question, these steps would be used in a logical order (in the order given above). The questions were therefore given in this order in the Part B question paper. The questions involving visualisation of three-dimensional structures of molecules were given first, followed by the questions involving rotation, and finally the questions involving reflection. The Part B question paper is given in Appendix 1 (page 144).

Some of the questions in Part B have more than one section. Question 1 (page 145), for example, has three sections. For each section, one mark was awarded for a correct answer, and 0 for an incorrect answer. Hence the maximum possible score for questions 1, 4, 5, 6 and 7 is three marks each, and for questions 2 and 3 it is two marks each. For Questions 8 - 33, one mark was awarded for each correct answer. The maximum possible score for Part B is hence 45.

The scores are tabulated in Table 4.7. Each student is identified by the same number and initials as in Table 4.3. The scores for each question follow in columns 3 - 47. The scores for questions involving visualisation of three-dimensional structures of molecules are given first, and these are followed successively by the scores for questions involving rotation and reflection. In the final column, the student's total score is recorded (the maximum possible score is 45). In the final row, the total number of students who answered each question correctly is given; this is the sum of the scores in each column. For example, four students answered question 1(i) correctly. Subtotals for the experimental and control groups are also given, in rows 17 and 33 respectively.

Table 4.7
Pretest results - Part B

	number	initials	Question 1 (i)	Question 1 (ii)	Question 1 (iii)	Question 2 (i)	Question 2 (ii)	Question 3 (i)	Question 3 (ii)	Question 4 (i)	Question 4 (ii)	Question 4 (iii)	Question 5 (i)	Question 5 (ii)	Question 5 (iii)	Question 6 (i)	Question 6 (ii)	Question 6 (iii)	Question 7 (i)	Question 7 (ii)	Question 7 (iii)	Question 8	Question 9	Question 10
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
experimental group	1	M.C.	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
	2	G.M.	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1
	3	S.K.	0	0	0	1	1	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0	1	0
	4	B.R.	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
	5	N.M.	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
	6	I.M.	0	0	0	0	1	0	1	0	0	0	0	1	0	1	0	0	1	0	0	1	1	0
	7	D.D.	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
	8	T.M.	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
	9	O.R.	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0
	10	M.K.	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	11	M.S.	0	0	0	0	1	1	1	1	0	1	1	1	1	1	0	0	1	0	0	1	1	1
	12	H.T.	0	0	0	1	1	0	1	1	0	1	1	1	1	1	0	0	1	1	1	1	0	0
	13	F.M.	1	1	0	0	1	1	1	0	1	0	1	1	1	1	1	0	0	0	0	1	0	0
	14	N.S.	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	1	0	0	0	0	1
	15	L.G.	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1
	16	R.P.	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
	Subtotals		2	5	1	11	12	14	15	12	11	12	13	14	13	15	9	8	14	9	9	6	7	5
control group	17	L.S.	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
	18	G.R.	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1
	19	M.L.	0	0	0	1	1	1	1	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0
	20	S.M.	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	21	J.M.	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	22	J.M.	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0
	23	P.T.	0	0	0	0	1	1	1	0	0	0	1	0	0	1	1	1	1	1	1	0	0	0
	24	A.M.	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1
	25	L.M.	0	0	0	0	0	0	0	1	1	1	0	0	0	1	0	0	1	0	0	0	1	0
	26	M.M.	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
	27	M.K.	0	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1
	28	L.M.	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1
	29	T.M.	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0
	30	B.M.	0	0	0	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
	31	A.M.	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	Subtotals		2	4	0	11	12	13	13	12	12	13	14	13	13	15	12	12	13	11	10	7	8	6
	Totals		4	9	1	22	24	27	28	24	23	25	27	27	26	30	21	20	27	20	19	13	15	11

Table 4.7 (continued)

	number	initials	Question 11	Question 12	Question 13	Question 14	Question 15	Question 16	Question 17	Question 18	Question 19	Question 20	Question 21	Question 22	Question 23	Question 24	Question 25	Question 26	Question 27	Question 28	Question 29	Question 30	Question 31	Question 32	Question 33	Total
			25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
experimental group	1	M.C.	1	0	0	0	0	0	0	1	1	0	0	1	0	1	0	0	0	1	0	1	0	0	0	13
	2	G.M.	1	1	1	1	1	1	1	1	1	0	0	0	1	1	0	1	0	0	1	0	0	0	1	31
	3	S.K.	0	0	1	0	0	0	1	1	0	0	0	1	1	1	0	0	1	0	1	1	0	0	0	22
	4	B.R.	1	0	0	1	0	0	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	0	0	28
	5	N.M.	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	8
	6	T.M.	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	1	1	11
	7	D.D.	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	1	1	1	21
	8	T.M.	0	0	1	0	0	1	0	0	1	1	0	1	0	1	0	1	0	0	0	0	0	0	0	25
	9	O.R.	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0	24
	10	M.K.	0	1	1	1	0	0	0	0	0	1	1	0	1	1	0	1	1	0	0	0	1	0	0	29
	11	M.S.	0	0	1	1	0	1	0	1	1	1	1	0	1	1	0	0	0	0	1	1	0	0	1	24
	12	N.M.	0	0	0	0	0	1	1	1	1	0	0	0	1	1	1	1	1	0	0	0	1	0	1	21
	13	F.M.	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	1	1	1	0	20
	14	N.S.	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	0	0	0	1	0	0	31
	15	L.G.	0	1	1	1	0	0	1	1	1	0	0	0	1	1	0	0	1	1	1	1	0	1	1	30
	16	R.P.	0	0	0	0	0	0	1	1	0	0	0	1	0	1	0	1	1	0	0	1	0	1	1	28
	Subtotals		4	5	9	6	2	7	7	11	8	5	4	6	8	14	2	11	10	3	4	9	5	5	7	366
control group	17	L.S.	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0	0	1	0	0	18
	18	G.R.	1	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	28
	19	M.L.	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	1	0	0	1	12
	20	S.M.	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	1	1	0	0	0	0	34
	21	J.M.	0	1	1	1	1	1	1	1	0	1	0	1	1	1	0	1	1	1	1	1	1	1	1	34
	22	J.M.	1	0	0	1	0	0	1	0	0	0	0	0	0	1	0	1	0	0	0	1	1	0	1	26
	23	P.T.	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	13
	24	A.M.	1	0	1	1	1	1	1	1	1	0	1	0	1	1	0	0	1	0	0	0	0	0	1	31
	25	L.M.	1	1	1	0	0	1	1	0	0	0	1	0	1	1	0	0	0	0	1	1	1	0	1	19
	26	M.M.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	0	1	21
	27	M.K.	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	1	1	0	0	0	0	1	16
	28	L.M.	0	0	1	0	0	1	0	0	0	1	0	0	0	1	0	0	1	1	0	0	0	0	0	19
	29	T.M.	1	0	0	1	0	0	1	0	0	1	0	0	1	1	0	1	1	0	0	0	1	1	1	26
	30	B.M.	1	1	1	1	0	1	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	25
	31	A.M.	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	0	1	0	0	32
	Subtotals		8	6	8	8	4	7	8	5	6	5	4	4	9	9	1	7	10	5	4	5	8	2	8	354
	Totals		12	11	17	14	6	14	15	16	14	10	8	10	17	23	3	18	20	8	8	14	13	7	15	720

4.7. Analysis of the results of the pretest for Part B questions

4.7.1. Calculation of mean values and standard deviations

The mean of the raw scores for the experimental group was 23,0 from a possible maximum of 45. This is equivalent to 51%. The mean score for the control group was 24,5 or 54%. The variance (s^2) was 51,8 for the experimental group and 56,2 for the control group. These results are summarised in Table 4. 8. The variances are homogeneous; parametric statistical tests are therefore appropriate.

Table 4.8

The Mean Scores and the Standard Deviation of Part B results - Pretest

	Experimental group	Control group
N	16	15
$\bar{x}$	23,0	24,5
$\bar{x}$(%)	51,1	54,4
s	7,2	7,5
s^2	51,8	56,2

4.7.2. Description of the results

The Part B questions were designed to test students' competence in each component step required for the solution of the Part A questions. Students would fail Part A questions if they were unable to perform one or more of the component steps required for the solutions. The component steps tested in Part B were mainly:

(a) the use of depth cues for the visualisation of the three-dimensional structures of molecules;

(b) the meaning of some of the special words and phrases used in the questions;

(c) the correct identification of the various axes and planes;

(d) the visualisation of the positions of atoms after the operations of rotation and reflection.

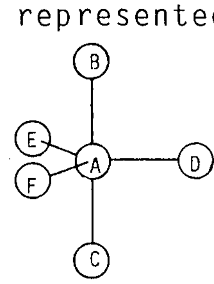
Let us now consider students' competence in these component steps, by analysing their responses to some of the questions given in Part B of the question paper.

(a) <u>Students' competence in the use of depth cues for the visualisation of the three-dimensional structures of molecules</u>

Students competence in the use of the various depth cues was tested in questions 1 - 7 in Part B of the question paper (see pages 145 - 148).The overlap cue was isolated in question 1, and about 90% of students had difficulty with this question. However, about 80% of students responded correctly to the foreshortening of lines and distortion of angles cues (questions 2 and 3). About 80% of students could visualise correctly molecules represented by ball and stick formulae when all the depth cues were present (questions 4 and 5), and 75% could visualise molecules represented by dimensional formulae (questions 6 and 7). Questions 4 and 6, which are given below, are examples of questions used to test how competent students were in their ability to use depth cues to visualise three-dimensional structures. They test students' ability to use the depth cues of overlap, foreshortening of lines and distortion of angles (question 4); and wedge and dash cues (question 6) to determine which atoms in a molecule are (i) in the plane of the paper, (ii) closer to the viewer than the plane of the paper, and (iii) further away from the viewer than the plane of the paper.

<u>Question 4</u>

Consider the molecule represented below:



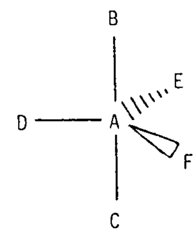
i) Which (if any) of the atoms B, C, D, E and F are not in the plane of the paper?

ii) Which (if any) of the atoms are closer to you than the plane of the paper?

iii) Which (if any) of the atoms are further away from you than the plane of the paper?

Question 6

Consider the molecule represented below:



i) Which (if any) of the atoms B, C, D, E and F are not in the plane of the paper?

ii) Which (if any) of the atoms are closer to you than the plane of the paper?

iii) Which (if any) of the atoms are further away from you than the plane of the paper?

From Table 4.7 it can be seen that about 30% of the students could not answer question 4, which involves the visualisation of a molecule represented by a ball and stick formula, while 35% of students had difficulty in visualising a molecule represented by a dimensional formula (question 6).

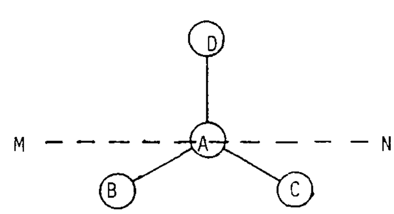
The ability to visualise the three-dimensional structure of a molecule, from its two-dimensional representation, is of fundamental importance. Those students who were unable to do this task cannot, of course, be expected to perform more complicated tasks which involve, in addition, the visualisation of the effects of rotation and reflection upon molecules. In fact, analysis of the students' answers revealed that the mean score for Part A questions of those students who answered these questions incorrectly was 20%. This is significantly lower, as shown by a t-test, than the mean of those students who answered these questions correctly (33%).

(b) Students' competence in the understanding of the meaning of some of the special words and phrases used in the questions

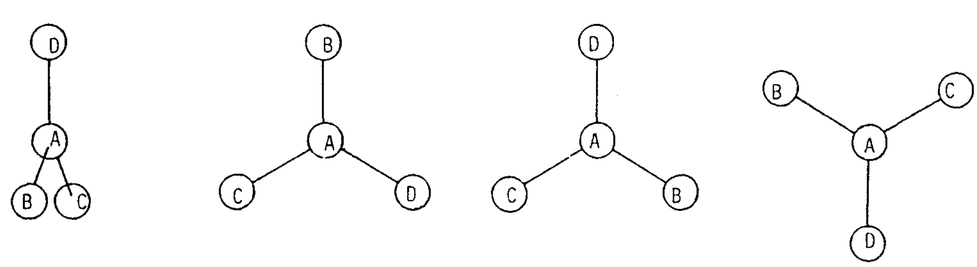
Some of the questions in Part B were designed to test students' understanding of some of the special words and phrases made use of in the Part A questions. Questions 8, 9 and 10 (page 149 - 150) can be made use of to test students' understanding of the words and phrases involving rotation, while questions 25, 26 and 27 (page 157 - 158) test students' understanding of words and phrases involving reflection. Each of these questions is similar to one of the Part A questions; the only difference being that simpler words are used. As an example, consider question 6 in Part A (page 134) and question 8 in Part B (page 149), which is reproduced below. Comparison of the answers to both these questions may provide information on students' understanding of the phrase "rotation about the X-axis".

Question 8

Consider the trigonal planar molecule represented in diagram 1 below:

1 

Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if you turned it around the axis corresponding to the dashed line MN?



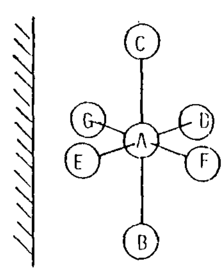
The only difference between this question and question 6 in Part A is in the words used. The words used in the Part A question are "Which one of the diagrams (2, 3, 4, or 5) shows what the molecule would look like if it were rotated about the X-axis?" In the Part B question the phrase "rotated about the X-axis" was replaced by "turned around the axis corresponding to the dashed line MN". A student who had difficulty with the Part A question but who answered the Part B question correctly, probably had difficulty with the phrase "rotated about the X-axis". The percentage of students who had difficulty with this phrase was about 25%.

A similar comparison of the answers to question 13 (Part A) and question 27 (Part B) (see below) showed that about 40% of the students had difficulty with the phrase "reflection in the YZ plane".

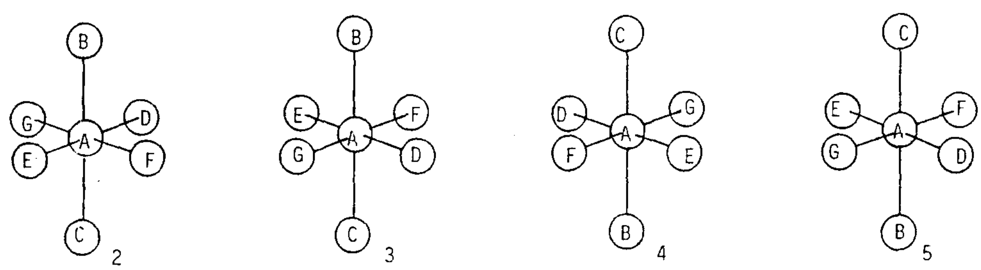
Question 27

A mirror perpendicular to the plane of the paper is placed to the left of an octahedral molecule as shown in diagram 1 below:

1



Which one of the diagrams (2, 3, 4 or 5) shows what the mirror image of the molecule would look like?

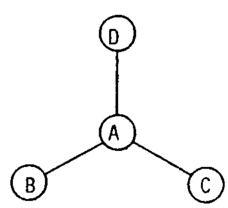


(c) Students' difficulties concerning the identification of the various axes and planes

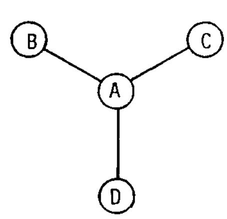
Some of the Part B questions were designed to test students' ability to identify the various axes and planes correctly. Only about 40% of students could identify the various axes (questions 11 - 13), while 30% could identify the planes (questions 28 - 30). Consider, for example, questions 11 and 28, which were designed to test students' ability to identify correctly the X-axis and the XY plane respectively.

Question 11

Consider the trigonal planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1 

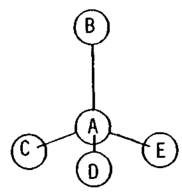
About which axis (X, Y or Z) must the molecule be rotated if it is to look like diagram 2?

2 

Question 28

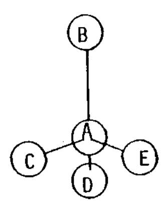
Consider the tetrahedral molecule represented in diagram 1 below. Atoms A and B are in the plane of the paper, atoms C and E are further away from you than the plane of the paper and atom D is closer to you than the plane of the paper.

1



In which plane (XY, XZ or YZ) must the molecule be reflected if it is to look like diagram 2?

2



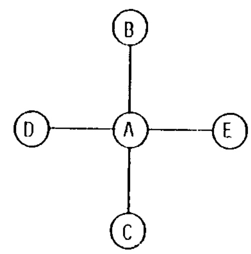
About 60% of students tested could not identify the X-axis (Question 11) while 75% could not identify the XY plane (Question 28).

(d) Difficulties concerning the visualisation of the positions of atoms after an operation

Some questions were set to test students' ability to visualise the positions of atoms after the rotation or the reflection of a molecule. Between 40% and 50% of students could visualise the positions of the atoms after rotation about the X- and Z-axes, and after reflection in the XY and YZ planes. Only about 20%, however, could visualise the positions of atoms after rotation about the Y-axis or after reflection in the XZ plane. Consider for example questions 15 and 32, reproduced below, which test respectively students' ability to visualise the positions of atoms after rotation about the Y-axis and after reflection in the XZ plane.

Question 15

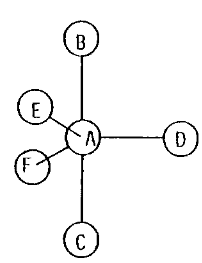
Consider the square planar molecule represented below, in which all the atoms are in the plane of the paper:



Which (if any) of the atoms A, B, C, D and E might not be in the plane of the paper if the molecule were rotated about the Y-axis?

Question 32

Consider the molecule represented below. Atoms A, B, C and D are in the plane of the paper, atom E is closer to you than the plane of the paper and atom F is further away from you than the plane of the paper:



Which atom would be closest to the top of the page if the molecule were reflected in the XZ plane?

About 80% of students could not visualise correctly the positions of the atoms after the operation of rotation about the Y-axis (Question 15), and 77% of the students had difficulty in visualising the positions of the atoms after the operation of reflection in the XZ plane (Question 32).

4.8. Reasons for students difficulties concerning three-dimensional visualisation of rotation and reflection

Many students failed the Part A questions concerning rotation about the various axes and reflection in the various planes, as shown in Table 4.6 (page 87).The reasons for their failure were established from an analysis of their answers to the Part B questions. If, for example, a student had difficulty with the questions involving rotation about the X-axis, his scores for the Part B questions that involved rotation about the X-axis were analysed. To illustrate specifically, consider, say, the results of student 1. M.C. (page 83). He obtained only one correct answer in the Part A questions concerning the X-axis. His Part B scores (see pages 89 and 90) reveal that he had difficulty in identifying the X-axis and in visualising the three-dimensional structure of molecules using the depth cues: overlap, foreshortening of lines, distortion of angles, and wedge and dash notation (see questions 1 - 7). He understood the meaning of the words used in the questions (he answered question 28 correctly), but had difficulty in identifying the X-axis (see answer to question 12), and also in visualising the positions of atoms after rotation about the X-axis (see answer to question 14).

The responses of each student were analysed in the same way. It was found that all students had difficulty in one or more of the component steps.

So far a few of the questions in Part B, and students' performance in them, has been considered in some detail. A similar study was also made for the other questions in Part B. The results are tabulated in Table 4.9. The percentages of students from each group (experimental and control), as well as the total percentage, who had difficulty in performing each one of the aspects required for the solution to Part A questions are given. A student was assumed to have difficulty with a particular aspect if he/she answered one or more questions involving that aspect incorrectly. For example, the percentage of the students in the experimental group who were unable to visualise a molecule represented by a ball and stick formula correctly (Questions 4 and 5) was 44%.

Table 4.9

Percentages of students who had difficulty with each of the aspects tested by Part B questions

Source of difficulty	Q*	exp. group	control group	total
1. Incorrect visualisation of molecule represented by a ball and stick formula	4 5	44	27	35
2. Incorrect visualisation of a molecule represented by a dimensional formula	6 7	50	33	42
3. Confusion concerning the meaning of the phrase "rotation about an axis"	8 9 10	50	40	45
4. Confusion concerning the meaning of the phrase "reflection in a plane"	25 26 27	75	33	55
5. Incorrect identification of the X, Y or Z axis	11 12 13	88	67	77
6. Incorrect identification of the XY, XZ or YZ plane	28 29 30	94	93	94
7. Incorrect visualisation of the positions of atoms after an operation of rotation	14 15 16	88	73	81
8. Incorrect visualisation of the positions of atoms after an operation of reflection	31 32 33	94	87	90
9. Incorrect visualisation of the overlap cue after an operation of rotation	17 18	56	73	65
10. Incorrect visualisation of the foreshortening of lines after an operation of rotation	19 20	75	87	81
11. Incorrect visualisation of the distortion of angles after an operation of rotation	21 22	94	93	94
12. Incorrect visualisation of wedge and dash notation after an operation of rotation	23 24	56	60	58

Note: Q* = Numbers of Part B questions which tested each step.

As can be seen from Table 4.9 less than 45% of the students had difficulty with using the depth cues to visualise the three-dimensional structure of molecules. This aspect was thus performed better than the other aspects which were tested. This was to be expected, since this task was simpler than the others: it did not involve the visualisation of the effects of operations upon molecules.

77% of the students could not identify the orientation of the X-, Y- and Z-axes, even though a diagram giving this information was given at the top of each page in the question paper. Nearly all the students had difficulty in identifying the planes and in the visualisation of the positions of the atoms after an operation of rotation or reflection. In addition, many students could not visualise the various depth cues after an operation of rotation.

4.8.1. Students' recognition of depth cues

In some of the Part B questions (questions 1, 3, 5 and 7, pages 145 - 148) students were asked to state the depth cues that were made use of in the diagrams. The percentages of the students who recognised cues correctly were:

38% for the overlap cue
34% for foreshortening of lines
49% for distortion of angles
49% for wedge and dash notation.

25% of the students did not identify any depth cues, while 49% gave incorrect explanations in some cases, displaying evidence of misconceptions. In Question 1 (page 145) the diagrams use overlap as the only depth cue, and it is specified that bond lengths may not be equal. However, eight students did not see the overlap cue, but thought that the bond lengths provided clues. Two students thought that all the atoms were in the plane of the paper if the bond lengths were equal, or, conversely, that bond lengths that were not equal signified that atoms were not in the plane of the paper. A greater bond length was thought by two students to denote an atom closer to the viewer than the plane of the paper, and by four students to denote an atom further away from the viewer than the plane of the paper. The size of the angles was also thought to be a cue; five students thought that atoms are not in the plane if angles are not equal.

In question 3 (page 146),one student thought that all atoms were in the plane of the paper, since the molecule was described as square planar. In question 5 (page 147) three students thought that the directions in which bonds were drawn provided a cue: atoms pointing towards the bottom of the page were thought to be further away than the plane of the paper. In question 7 (page 148) one student thought that meant that the bond was going into the plane of the paper, while meant that the bond was coming out of the plane of the paper.

In questions 18, 20, 22 and 24 (pages 154 - 157), students were asked to identify depth cues after an operation of rotation, and to provide explanations for their answers. The percentages of students who identified each cue correctly were:

32% for overlap
40% for foreshortening of lines
17% for distortion of angles.

21% gave no explanations, and 66% gave incorrect explanations. In diagrams in which only the overlap cue varied, 2 students thought that the bond angles varied and one student thought that the bond lengths varied. Five students could not distinguish between variation in bond angles and variation in bond lengths. Six students thought that the bond lengths would appear to remain the same during rotation, while twenty (65%) thought that the angles would appear to remain the same. Four students could not distinguish between the diagrams and stated that all the diagrams were the same.

4.9. Conclusion

From the results discussed in this chapter, it is clear that the students who were tested had serious difficulty with the three-dimensional visualisation of the operations of rotation and reflection. The results to the Part B questions showed that their difficulty was due to lack of competence in many of the component steps needed for the solution to the standard problems which were tested in the Part A questions. Teachers of chemistry generally assume that students are familiar with the depth cues which are present in molecules represented by ball and stick formulae, although they often teach students the meaning of wedge and dash notation used in dimensional formulae. The results of this study show that it would be advisable for teachers to check whether their students are competent in the use of the depth cues. If the students are not competent, then the correct use of the depth cues should be taught to the students when the representations are introduced to them. Competence in all the depth cues, and all the other component steps, is needed if students are to master the skill of three-dimensional visualisation. Instruction on the various steps may be necessary. The remedial instruction programme was planned according to these results. It will be discussed in Chapter 5.

CHAPTER 5

REMEDIAL INSTRUCTION

5.1. Introduction

This chapter outlines the remedial instruction programme which was given to the experimental group of students in the form of a workshop. The results of Part B of the pretest (see pages 89 and 90) indicated that students' difficulties in spatial visualisation are primarily due to lack of sufficient competence in some very simple basic concepts and skills. The most important of these was the lack of understanding or appreciation of depth cues. Other aspects that caused difficulty were lack of understanding of the orientation of the axes, of the terms used in the questions and of the operations of rotation and reflection. Each of these aspects was therefore taught in the remedial programme. An outline of the aspects included in the remedial programme is presented in Table 5.1.

Table 5.1
Aspects taught in the remedial programme.

1. Introduction to the sources of difficulty
2. Orientation of the various axes (X, Y and Z)
3. Orientation of the various planes (XY, XZ and YZ)
4. Explanation of the depth cues generally made use of to represent three-dimensional structures
    - 4.1. the overlap cue
    - 4.2. foreshortening of lines
    - 4.3. distortion of angles
    - 4.4. wedge and dash notation
5. Explanation of the operations of rotation and reflection
    - 5.1. Rotation about the various axes (X, Y and Z)
    - 5.2. Reflection in the various planes (XY, XZ and YZ)

The complete set of notes given to the students is presented in Appendix 2 (page 193).

5.2. Design of the instruction programme

In this section the instruction programme is explained. The scope, diagrams and organisation of the programme are discussed.

5.2.1. Scope of the programme

The programme gave instruction on those aspects of three-dimensional visualisation that were found in Part B of the pretest to cause difficulty. Instruction was given on the orientation of each axis and plane, the use of the depth cues, and the operations of rotation and reflection. Instruction focused on one step at a time, and was as simple and short as possible. A logical set of simple rules for solving three-dimensional visualisation problems was given to the students.

5.2.2. Diagrams in the programme

The following structures were used in the programme:

linear
angular (120°)
square pyramidal
seesaw
T-shaped
trigonal pyramidal

It can be seen that, with the exception of T-shaped molecules, the structures used were different from those used in the tests. This was deliberately done to avoid the possibility of students correctly answering the post-test questions because of their remembering (without understanding) the correct answers to the exercises in the instruction programme.

The final exercise (Exercise 7, page 211) used questions 1 and 10 which appear in Part A of the pretest (pages 132 and 136) to give practice in rotation and reflection. Since these questions were in the pretest, they were not given in the post-test.

One of the aims of the instruction programme was to help students visualise molecules three-dimensionally without using models. Though models were used in the teaching of each aspect, they were not allowed when students had to work through the exercises.

5.3. Administration of the programme

5.3.1. Division of the students into groups

The remedial instruction workshop was held on 16 September 1988. The students in the second year chemistry class were divided randomly into two groups, and were told on arrival which group they were in. The experimental group was given the instruction programme, which was completed in a ninety minute session with a five minute break in the middle of the session. During this time, the control group had a workshop on the skills required for dealing with relationships between variables. Thus all the students were involved; this would minimise the Hawthorne effect (see page 49).

5.3.2. Teaching aids

Each student was given a mirror and three models. One model was of a T-shaped molecule, the second was of a linear diatomic molecule, and the third was of the X-, Y- and Z-axes. Together with the set of notes presented in Appendix 2, these were the only teaching aids used. The cost of the programme was therefore very low. The molecular models consisted of spheres of different colours, which could be referred to during the programme. They were made from a set of Gallenkamp Linnell molecular models MTH 680.

5.3.3. Organisation of the programme

Each topic was introduced by teaching, with the help of examples. After each topic was explained, the students worked through the exercises on their own. The answers to the exercises were given on the right hand column of the page (see for example exercise 1, page 196). The students covered the right hand column with a piece of paper until they had tried the exercises, then checked their answers.

The post-test was administered one week after the students had completed the instruction programme.

CHAPTER 6

RESULTS OF THE POST-TESTS AND THEIR ANALYSIS

6.1. Introduction

After the remedial instruction programme, discussed in Chapter 5, post-tests were given to both the experimental and control groups, in order to assess the effectiveness of the remedial programme. In this chapter the results of the post-tests are presented and analysed.

6.2. Results of the Post-tests

6.2.1. Results of the post-test: Part A questions

These results are tabulated in Table 6.1; they are presented in the same form as the pretest results in Table 4.3.

6.2.2. Results of the post-test: Part B questions

These results are presented in Table 6.2; they are presented in the same form as the pretest results in Table 4. 7.

6.3. Reliability of the Post-test

The reliability coefficient was calculated for Part A of the post-test in the manner described in Section 4.5.1 (see page 84). Table 6.3 shows how the two halves of the test were constituted.

Table 6.1

Post-test results - Part A

	number	initials	Q12, X-axis, B.S.	Q10, X-axis, B.S.	Q18, X-axis, D.F.	Q21, X-axis, D.F.	Q5, Y-axis, B.S.	Q17, Y-axis, B.S.	Q5, Y-axis, D.F.	Q14, Y-axis, D.F.	Q22, Z-axis, B.S.	Q9, Z-axis, B.S.	Q8, Z-axis, D.F.	Q16, Z-axis, D.F.	Q24, XY plane, B.S.	Q23, XY plane, B.S.	Q6, XY plane, D.F.	Q13, XY plane, D.F.	Q20, XZ plane, B.S.	Q2, XZ plane, B.S.	Q4, XZ plane, D.F.	Q19, XZ plane, D.F.	Q3, YZ plane, B.S.	Q15, YZ plane, B.S.	Q1, YZ plane, D.F.	Q11, YZ plane, D.F.	Total score
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
experimental group	1	M.C.	0	1	1	1	0	1	1	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	1	0	9
	2	G.M.	1	1	1	1	1	1	1	1	0	0	1	1	0	1	0	1	0	0	0	0	1	0	1	0	14
	3	S.K.	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	0	13
	4	B.R.	1	1	1	1	1	1	1	1	0	0	1	0	0	1	0	1	0	0	0	0	1	0	0	0	12
	5	N.M.	1	0	1	1	1	1	1	1	0	0	1	1	0	1	1	0	0	1	0	0	1	1	1	0	15
	6	I.M.	1	1	1	1	1	1	1	1	0	1	0	1	0	0	0	0	0	1	0	0	1	1	0	0	13
	7	D.D.	1	1	1	1	1	0	0	1	1	0	0	1	0	1	1	0	1	1	1	1	1	1	1	1	18
	8	T.M.	0	0	1	1	1	1	1	1	0	0	1	1	0	0	0	0	1	1	0	0	1	0	1	0	12
	9	O.R.	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	1	0	1	0	9
	10	M.K.	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	0	1	1	1	1	21
	11	M.S.	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0	1	0	0	1	0	1	1	17
	12	H.T.	1	1	1	1	1	1	0	1	1	0	0	1	0	0	1	0	0	1	0	0	1	1	1	0	14
	13	F.M.	1	1	1	1	1	0	0	1	0	0	0	0	0	0	1	0	1	1	0	0	1	1	1	0	12
	14	N.S.	1	1	1	1	1	1	1	0	0	1	1	1	1	0	1	1	1	1	0	0	1	1	0	0	17
	15	L.G.	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	9
	16	R.P.	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	0	1	1	21
	Subtotals		12	13	16	15	14	12	12	13	5	4	9	11	5	8	10	6	8	11	1	2	14	8	13	4	226
control group	17	L.S.	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0	0	0	1	1	0	1	0	15
	18	G.R.	1	0	0	0	1	0	1	0	0	1	1	0	0	0	0	1	0	0	0	0	1	0	1	0	8
	19	M.L.	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	4
	20	S.M.	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	1	0	0	1	6
	21	J.M.	1	1	1	1	0	1	1	1	1	0	1	1	0	0	0	0	1	1	1	0	1	0	1	0	15
	22	J.M.	0	0	0	1	1	0	1	1	0	1	0	0	1	1	0	0	0	0	0	0	0	0	1	0	8
	23	P.T.	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	6
	24	A.M.	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	10
	25	L.M.	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	1	1	6
	26	M.M.	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	1	0	1	0	6
	27	M.K.	1	0	1	1	0	1	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	0	1	0	10
	28	L.M.	0	0	0	1	1	0	1	1	1	1	0	0	0	0	0	0	1	0	0	0	1	1	1	1	11
	29	T.M.	1	0	1	1	1	1	1	1	0	0	1	1	0	0	1	0	0	0	0	0	1	0	0	0	11
	30	B.M.	1	1	0	1	1	1	1	1	0	0	1	1	0	0	0	0	1	1	1	0	0	1	0	0	13
	31	A.M.	1	1	1	1	0	1	1	1	1	0	1	1	1	0	1	1	1	1	0	0	0	0	0	0	15
	Subtotals		7	4	6	10	10	9	10	10	4	5	9	7	3	4	3	2	6	5	4	1	10	2	9	4	144
	Total		19	17	22	25	24	21	22	23	9	9	18	19	8	12	13	8	14	16	5	3	24	10	21	8	370

Table 6.2
Post-test results - Part B

	number	initials	Question 1 (i)	Question 1 (ii)	Question 1 (iii)	Question 2 (i)	Question 2 (ii)	Question 3 (i)	Question 3 (ii)	Question 4 (i)	Question 4 (ii)	Question 4 (iii)	Question 5 (i)	Question 5 (ii)	Question 5 (iii)	Question 6 (i)	Question 6 (ii)	Question 6 (iii)	Question 7 (i)	Question 7 (ii)	Question 7 (iii)	Question 8	Question 9	Question 10
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
experimental group	1	M.C.	1	0	0	1	1	0	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0
	2	G.M.	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	3	S.K.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
	4	B.R.	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	5	N.M.	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	6	I.M.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	7	D.D.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	8	T.M.	0	1	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
	9	O.R.	0	1	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	0	0	0
	10	M.K.	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	11	M.S.	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0	1	1	1
	12	H.T.	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	13	F.M.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	14	N.S.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	15	L.G.	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	16	R.P.	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Subtotals		8	13	7	15	15	13	13	14	15	14	15	15	15	16	15	15	16	15	15	13	13	9
control group	17	L.S.	0	0	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
	18	G.R.	0	1	0	0	0	0	1	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1
	19	M.L.	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	0	0	1
	20	S.M.	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	0
	21	J.M.	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	22	J.M.	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	23	P.T.	1	1	0	1	1	1	1	0	1	1	0	1	1	0	0	0	0	0	0	1	1	0
	24	A.M.	0	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1
	25	L.M.	0	1	0	0	0	1	1	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0
	26	M.M.	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
	27	M.K.	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0
	28	L.M.	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	29	T.M.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	30	B.M.	0	0	0	0	0	1	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1
	31	A.M.	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Subtotals		6	12	4	11	11	13	13	11	12	12	10	13	14	13	12	12	14	13	13	11	12	8
	Totals		14	25	11	26	26	26	26	25	27	26	25	28	29	29	27	27	30	28	28	24	25	17

Table 6.2 (continued)

	number	initials	Question 11	Question 12	Question 13	Question 14	Question 15	Question 16	Question 17	Question 18	Question 19	Question 20	Question 21	Question 22	Question 23	Question 24	Question 25	Question 26	Question 27	Question 28	Question 29	Question 30	Question 31	Question 32	Question 33	Total score
			25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
experimental group	1	M.C.	1	1	1	0	0	0	1	1	0	1	0	1	0	0	0	1	1	0	0	1	0	0	0	22
	2	G.M.	1	1	1	1	1	1	0	1	1	0	1	0	1	1	1	1	0	1	1	0	1	1	0	37
	3	S.K.	1	1	1	1	1	0	1	1	1	0	0	0	1	1	0	0	1	1	1	0	1	1	0	34
	4	B.R.	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	35
	5	N.M.	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	1	26
	6	I.M.	1	1	1	1	1	1	1	1	1	0	0	0	1	1	0	0	0	1	1	1	0	1	0	37
	7	D.D.	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	43
	8	T.M.	1	1	1	1	1	0	1	0	1	1	1	0	1	1	1	1	0	0	1	0	0	1	1	30
	9	O.R.	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	1	1	1	1	1	23
	10	M.K.	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	0	1	0	1	1	1	1	1	37
	11	M.S.	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	0	1	0	1	1	0	32
	12	H.T.	1	1	1	1	1	0	1	1	0	0	0	1	1	1	0	0	1	0	1	0	1	0	1	33
	13	F.M.	1	1	1	1	1	0	1	1	1	1	1	0	1	1	0	0	1	0	0	0	1	1	1	38
	14	N.S.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	44
	15	L.G.	1	1	1	1	1	0	0	1	0	0	1	0	0	0	1	0	0	1	0	0	1	0	1	30
	16	R.P.	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	42
	Subtotals		13	15	15	14	14	7	12	13	9	6	7	6	12	12	10	9	9	9	12	8	11	11	10	543
control group	17	L.S.	1	0	0	0	1	0	0	1	0	1	1	0	1	1	1	0	1	1	0	0	0	0	1	29
	18	G.R.	1	1	1	0	0	1	1	1	0	0	0	0	0	0	1	0	1	1	1	0	0	0	1	25
	19	M.L.	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	16
	20	S.M.	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	0	0	1	1	0	34
	21	J.M.	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	0	0	0	1	1	1	1	0	38
	22	J.M.	1	1	0	0	1	0	0	0	0	0	1	0	1	1	0	0	0	1	1	1	0	0	1	29
	23	P.T.	1	1	1	1	1	0	0	0	1	1	0	0	0	1	0	0	0	0	1	0	1	0	0	22
	24	A.M.	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	0	0	1	0	0	0	1	1	33
	25	L.M.	0	1	1	1	1	1	0	1	1	1	0	1	0	0	0	0	0	0	0	1	0	0	1	18
	26	M.M.	0	0	0	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	1	0	0	1	1	24
	27	M.K.	0	1	1	0	1	0	1	1	0	0	0	0	1	1	0	1	0	1	1	1	1	1	1	32
	28	L.M.	1	0	1	1	1	1	0	0	0	0	1	1	1	1	1	0	0	0	1	0	1	1	1	34
	29	T.M.	0	1	1	1	1	0	1	1	0	0	1	0	1	1	0	0	1	1	1	1	1	1	1	37
	30	B.M.	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	0	0	0	0	0	0	0	1	28
	31	A.M.	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	0	0	0	0	0	36
	Subtotals		10	11	11	8	12	8	9	10	8	8	5	4	11	11	8	3	5	8	8	5	6	7	11	435
	Totals		23	26	26	22	26	15	21	23	17	14	12	10	23	23	18	12	14	17	20	13	17	18	21	978

Table 6.3.

Division of the Post-test (Part A) into halves

	Question numbers
1st half	1, 6, 7, 12, 13, 16, 17, 19, 20, 21, 22, 23
2nd half	2, 3, 4, 5, 8, 9, 10, 11, 13, 14, 18, 24

The reliability coefficient, r_c was found to be 0,90. This indicates a very significant degree of reliability ($p < 0{,}001$). The reliability of the post-test was found to be higher than that of the pretest. This suggests that students' visualisation ability had improved, leading to less random guessing, especially for the experimental group.

6.4. Comparison of pretest and post-test results

(a) Part A questions

Table 6.4 contains a summary of the results of the Part A questions; it compares each student's score in the pretest and in the post-test. Columns 1, 2 and 3 give respectively the students' numbers, initials and sex. M denotes a male student, F a female student. Columns 4 and 5 give each student's total for questions involving rotation. Column 4 gives the pretest result and column 5 the post-test result. Columns 6 and 7 give respectively the pretest and post-test results for questions involving reflection. The maximum score possible in each case is 12. Columns 8 and 9 give respectively each student's total score in the pretest and post-test. The maximum possible score is 24. These total scores are expressed as percentages in columns 10 and 11.

(b) Part B questions

A summary of the results of the Part B questions is given in Table 6.5. The first three columns give the students' numbers, initials and sex. Columns 4 and 5 give the students' scores for all questions testing students' ability to visualise the three-dimensional structures of molecules using the various depth cues, for the pretest and post-test respectively. The maximum possible score is 19. In columns 6 and 7 the students' scores for all questions involving rotation are given for the pretest and post-test respectively, the maximum possible score being 17. Columns 8 and 9 give similarly the scores for all questions involving reflection, the maximum score possible being 9. The students' total scores for Part B are given in columns 10 and 11, and are expressed as percentages in columns 12 and 13. (The maximum possible score is 45.)

From Table 6.4 it can be seen that the experimental group (numbers 1 - 16) improved significantly ($p < 0{,}01$) in the visualisation of the operations of rotation and reflection, whereas there was no significant improvement in the control group (numbers 17 - 31). From Table 6.5 it can be seen that the experimental group improved significantly ($p < 0{,}01$) in the component steps which are involved in the visualisation of the three-dimensional structure of a molecule, and on the steps which are involved in the visualisation of the operations of rotation and reflection. The control group improved significantly in the steps which are involved in the visualisation of rotation, but not in the other steps. These results will be analysed in more detail in the next section.

6.5. Analysis of the results of the post-test for Part A questions

The mean value and the standard deviation of the scores are summarised in Table 6.6. The mean value for the experimental group was calculated to be 14,1 and for the control group it was 9,6 (the maximum score possible is 24). The standard deviation of the results for the experimental group was 3,8, and for the control group it was 3,7.

Table 6.4

Comparison of pretest and post-test results - Part A

	Number	Initials	Sex	Rotation pretest	Rotation post-test	Reflection pretest	Reflection post-test	Total pretest	Total post-test	Percentage pretest	percentage post-test
	1	2	3	4	5	6	7	8	9	10	11
experimental group	1	M.C.	M	4	6	1	3	5	9	21	38
	2	G.M.	M	2	10	2	4	4	14	17	58
	3	S.K.	F	3	11	1	2	4	13	17	54
	4	B.R.	F	7	9	3	3	10	12	42	50
	5	N.M.	F	1	9	2	6	3	15	13	63
	6	I.M.	M	1	10	3	3	4	13	17	54
	7	D.D.	M	0	8	1	10	1	18	4	75
	8	T.M.	F	5	8	3	4	8	12	33	50
	9	O.R.	M	7	1	4	8	11	9	46	38
	10	M.K.	M	9	11	2	10	11	21	46	88
	11	M.S.	M	6	10	2	7	8	17	33	71
	12	H.T.	M	2	9	3	5	5	14	21	58
	13	F.M.	F	1	6	3	6	4	12	17	50
	14	N.S.	F	8	10	5	7	13	17	54	71
	15	L.G.	M	4	7	2	2	6	9	25	38
	16	R.P.	M	2	11	2	10	4	21	17	88
	Totals			62	136	39	90	101	226		
control group	17	L.S.	M	2	9	3	6	5	15	21	63
	18	G.R.	M	6	5	4	3	10	8	42	33
	19	M.L.	M	2	2	3	2	5	4	21	17
	20	S.M.	M	5	3	6	3	11	6	46	25
	21	J.M.	M	6	10	7	5	13	15	54	63
	22	J.M.	F	3	5	4	3	7	8	29	33
	23	P.T.	F	1	4	5	2	6	6	25	25
	24	A.M.	M	12	7	3	3	15	10	63	42
	25	L.M.	F	6	3	3	3	9	6	38	25
	26	M.M.	M	4	2	3	4	7	6	29	25
	27	M.K.	F	0	8	1	2	1	10	4	42
	28	L.M.	F	4	6	3	5	7	11	29	46
	29	T.M.	M	8	9	1	2	9	11	38	46
	30	B.M.	M	9	9	0	4	9	13	38	54
	31	A.M.	M	4	10	4	5	8	15	33	63
	Totals			72	92	50	52	122	134		

Table 6.5

Comparison of pretest and post-test results - Part B

	Number	Initials	Sex	Visualisation pretest	Visualisation post-test	Rotation pretest	Rotation post-test	Reflection pretest	Reflection post-test	Total pretest	Total post-test	Percentage pretest	Percentage post-test
	1	2	3	4	5	6	7	8	9	10	11	12	13
experimental group	1	M.C.	M	4	10	5	9	2	3	11	22	24	49
	2	G.M.	M	16	17	13	14	3	6	32	37	71	82
	3	S.K.	F	11	19	7	10	3	5	21	34	47	76
	4	B.R.	F	16	18	9	14	4	3	29	35	64	78
	5	N.M.	F	3	14	3	7	3	5	9	26	20	58
	6	I.M.	M	5	19	5	14	3	4	13	37	29	82
	7	D.D.	M	16	19	2	15	4	9	22	43	49	96
	8	T.M.	F	16	14	6	11	1	5	23	30	51	67
	9	O.R.	M	16	15	4	1	2	7	22	23	49	51
	10	M.K.	M	16	17	10	13	3	7	29	37	64	82
	11	M.S.	M	10	13	12	13	3	6	25	32	56	71
	12	H.T.	M	12	17	6	12	5	4	23	33	51	73
	13	F.M.	F	11	19	3	15	6	4	20	38	44	84
	14	N.S.	F	14	19	14	17	3	8	31	44	69	98
	15	L.G.	M	16	17	10	9	6	4	32	30	71	67
	16	R.P.	M	17	17	4	16	5	9	26	42	58	93
	Totals			199	264	113	190	56	89	368	543		
control group	17	L.S.	M	15	15	3	10	3	4	21	29	47	64
	18	G.R.	M	17	11	8	9	2	5	27	25	60	56
	19	M.L.	M	8	12	2	3	3	1	13	16	29	36
	20	S.M.	M	17	14	15	14	3	6	35	34	78	76
	21	J.M.	M	15	18	14	15	8	5	37	38	82	84
	22	J.M.	F	17	17	5	8	4	4	26	29	58	64
	23	P.T.	F	10	10	1	10	2	2	13	22	29	49
	24	A.M.	M	15	15	14	15	1	3	30	33	67	73
	25	L.M.	F	5	7	9	9	4	2	18	18	40	40
	26	M.M.	M	16	17	0	3	5	4	21	24	47	53
	27	M.K.	F	12	17	3	8	4	7	19	32	42	71
	28	L.M.	F	14	17	5	12	2	5	21	34	47	76
	29	T.M.	M	15	19	7	11	5	7	27	37	60	82
	30	B.M.	M	14	11	12	15	0	2	26	28	58	62
	31	A.M.	M	15	17	16	15	3	4	34	36	76	80
	Totals			205	217	114	157	49	61	368	435		

Table 6.6
The mean score ($\bar{x}$) and the standard deviation (s)
for the results to Part A questions

	Experimental group	control group
N	16	15
$\bar{x}$	14,13	9,60
s	3,84	3,70
$\bar{x}$ (%)	58,9	40,0

6.5.1. Effectiveness of the instruction programme

In order to assess the effectiveness of the instruction programme, an analysis of covariance (ANCOVA) was undertaken (see page 79), with pretest scores as covariates. The ANCOVA is summarised in Table 6.7.

Table 6.7
ANCOVA for Part A results for the experimental group
and the control group

source of variation	SS	df	MS	F	p
between groups	156,68	1	156,68		
within groups	411,35	28	14,69	10,67	<0,01
total	568,03	29			

Note: SS = sum of squares
df = degrees of freedom
MS = mean square

The critical value of F for (1, 28) degrees of freedom at the 0,01 level of significance is 7,64 (Weinberg and Goldberg, 1979, p. 531). The F value obtained (10,67) is hence significant at the 0,01 level. It can therefore be concluded that the remedial instruction programme was effective in improving students' ability to visualise the operations of rotation and reflection.

6.5.2. Percentages of students who failed questions concerning each axis or plane

Table 6.8 gives the percentages of students who failed each axis or plane (for analogous pretest results, see Table 4.6). This table also gives the pretest results, for comparison purposes.

Table 6.8
Percentages of students who failed questions concerning each axis or plane

axis or plane	experimental group		control group	
	pretest	post-test	pretest	post-test
X-axis	81	13	80	60
Y-axis	81	25	73	33
Z-axis	94	75	67	80
XY plane	100	75	87	87
XZ plane	100	88	100	93
YZ plane	81	63	73	93

From Table 6.8 it can be seen that the ability of the experimental group to visualise rotation and reflection improved for all axes and planes.

6.6. Analysis of the results of the post-test for Part B questions

The mean and the standard deviation for Part B of the post-test are given in Table 6.9, for both the experimental and the control groups.

Table 6.9

The mean value ($\bar{x}$) and the standard deviation (s) of the post-test results, Part B

	experimental group	control group
N	16	15
$\bar{x}$	33,93	29,00
s	6,61	6,81
$\bar{x}$ (%)	75,4	64,4

6.6.1. Percentages of students who had difficulty with each of the aspects tested by Part B questions

One of the main objectives of this research project is to identify the reasons for students' failure in tasks requiring three-dimensional thinking. Each test item in Part B of the question paper was designed to test students' competence in just one aspect required for success in three-dimensional thinking. These aspects are stated in column 1 of Table 6.10. In some cases, the comparison of the answers to different questions was needed in order to identify the aspects that caused difficulty. For example, the students' answers to question 6 (Part A) and question 8 (Part B) were compared in order to identify whether the students understood the meaning of the phrase "rotation about the X-axis". The table also shows the percentages of students, from the experimental group, who were incompetent in these operations initially (see pretest results - column 2) and after the remedial instruction programme (see post-test results - column 3). The figures in the table were obtained in the same manner as for Table 4. 9 (see page 100). A student was assumed to have difficulty if he/she answered one or more questions concerning a unit operation incorrectly.

From the table it can be seen that remedial instruction given to the experimental group was effective in improving the students' three-dimensional representation. Improvement was most marked for unit operations 2, 4 and 5, which involved the visualisation of the three-dimensional structure of molecules represented by dimensional formulae, the meaning of the words used in questions on reflection and the identification of axes, respectively. Almost all the students answered all the questions concerning the three-dimensional visualisation of the structure of a molecule correctly, both for ball and stick formulae and for dimensional formulae. Only two students were confused by the ball and stick representation, and one was confused by the dimensional formula. The students' ability to visualise the overlap cue and the wedge and dash cues improved more than their visualisation of the other cues. This result was to be expected because the instruction programme concentrated primarily on the overlap and wedge and dash cues.

Table 6.10

Percentages of students from the experimental group who had difficulty with some of the aspects tested by Part B questions before and after remedial instruction

Aspect	Q*	pretest	post-test
1. Ability to visualise a molecule represented by a ball and stick formula	4 5	44	13
2. Ability to visualise a molecule represented by a dimensional formula	6 7	50	6
3. Ability to understand the meaning of the phrase "rotation about an axis"	8 9 10	50	38
4. Ability to understand the meaning of the phrase "reflection in a plane"	25 26 27	75	31
5. Ability to identify the X, Y and Z axes	11 12 13	88	19
6. Ability to identify the XY, XZ and YZ planes	28 29 30	94	63
7. Ability to visualise the positions of atoms after an operation of rotation	14 15 16	88	56

Table 6.10 (continued)

Aspect	Q*	pretest	post-test
8. Ability to visualise the positions of atoms after an operation of reflection	31 32 33	94	63
9. Ability to visualise the overlap cue after an operation of rotation	17 18	56	31
10. Ability to visualise foreshortening of lines after an operation of rotation	19 20	75	75
11. Ability to visualise distortion of angles after an operation of rotation	21 22	94	81
12. Ability to visualise wedge and dash notation after an operation of rotation	23 24	56	25

Note: Q* = Numbers of the Part B questions which tested each step

6.7. Sociocultural factors that affect students' three dimensional visualisation ability

The review of the literature given in Chapter 1 indicated some studies which showed differences in the spatial visualisation ability of men and women (Maccoby and Jacklin, 1974; Tapley and Bryden, 1977), and also that certain cultural groups, particularly blacks, had inferior visualisation ability (Hudson, 1960, 1962a, 1962b; Mundy-Castle and Nelson, 1962; Vernon, 1965a, 1965b, Mundy-Castle, 1966). The conclusions from the present study concerning these aspects will now be considered.

6.7.1. Sex

Two null hypotheses were tested in order to ascertain whether, among second year chemistry students at Unibo, there was any difference in spatial visualisation ability between men and women.

H01: Male and female students visualise equally well the effects of the operations of rotation and reflection on diagrams of molecules.

H02: Male and female students visualise equally well the effects of the operations of rotation and reflection on diagrams of molecules, after they have undergone a remedial instruction programme.

These hypotheses were tested by t-tests. For the first hypothesis, the pretest results of all the students (in both the experimental and control groups) were used. Calculation using the equation (see page 77):

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}}$$

showed that t is 0,77.

Since the critical value of t for 29 degrees of freedom is 2,05 at the 0,05 level of significance, the null hypothesis can be accepted.

For the second hypothesis the post-test scores of the experimental group were used. Calculation showed that t = 0,59. This is not significant at the 0,05 level (the critical value of t is 2,15). Male and female students therefore performed the visualisation tasks equally well. In addition, both sexes benefited equally from instruction on three-dimensional visualisation.

6.7.2. Culture

All the students tested were black and most of them came from educationally disadvantaged backgrounds. Some researchers (Hudson, 1960, 1962a, 1962b; Mundy-Castle and Nelson, 1962; Vernon, 1965a, 1965b; Mundy-Castle, 1966) claim that people such as these are likely to have serious visualisation problems. The results of the pretest showed that their three-dimensional visualisation was indeed poor, although no comparisons with other cultural groups on the same tests are available. Visualisation tests administered to students at another university in South Africa, however, indicated that many white students had similar problems (Rochford, 1987a, 1989). The post-test results show that even one ninety-minute session of remedial instruction is enough to improve very significantly the students' ability to visualise the three-dimensional structure of a molecule using the depth cues, and to visualise the operations of rotation and reflection. These results indicate that any spatial visualisation difficulties found amongst black students are probably due to lack of training and experience. They are not due to an innate lack of ability, and can be easily overcome.

CHAPTER 7

REVIEW OF THE RESEARCH AND ITS MAIN CONCLUSIONS

In this concluding chapter, the aims and importance of this research programme will be reviewed, the main findings summarised, recommendations for the implementation of the research findings will be made, and finally, suggestions will be given for further research.

7.1. Importance of three-dimensional visualisation skills

Three-dimensional visualisation is a central and important skill in chemistry. Due to lack of competence in this skill, many students are seriously handicapped when they learn chemistry. Sufficient teaching time is seldom devoted to mastering this skill and many students perform poorly in chemistry as a result of their poor visualisation skills (Baker and Talley, 1972; Lord, 1985).

7.2. Main aims of the research

The main aims of this research were the following: to assess the level of Unibo students' three-dimensional visualisation skills, to find out the nature and extent of their difficulties, to identify reasons for the difficulties, and to devise teaching strategies that would help to overcome these difficulties and hence improve their visualisation skills.

7.3. Method of study

The study method adopted was the analysis of students' answers to carefully designed exercises. An experimental design was used. The students were divided into two groups: an experimental group and a Hawthorne effect control group. The research was restricted to the simpler aspects of three-dimensional thinking. It dealt only with rotation and reflection of simple molecules. The molecules were represented by two types of two-dimensional diagram: ball and stick formulae and dimensional formulae.

7.3.1. The test items

Two types of questions were designed. One type, which was given in Part A of the question paper, tested the overall ability of a student to answer correctly standard questions on rotation or reflection. In addition, in order to identify the reasons for failure, questions were designed to test students' competence in each of the component steps required for the solution of standard three-dimensional problems. These questions were given in Part B of the question paper. The rationale behind this is the hypothesis that the logical solution to a three-dimensional visualisation problem requires a stepwise approach. Each exercise in Part B tested, wherever possible, just one concept or skill. In some cases it was not possible to design a question that would test only one concept or skill. In these cases comparison of the answers to two or more questions was necessary in order to identify the aspects which caused difficulty. For example, the students' answers to question 6 (Part A) and question 8 (Part B) were compared in order to identify whether the students understood the meaning of the phrase "rotation about the X-axis" (see page 118).

The reliability of the tests was shown by the split-half measure to be good, especially for the post-test (see page 112). The content validity was ensured by designing at least two questions on each aspect.

The test items given to the students are given in Appendix 1; there were twenty-four items in Part A and thirty-three items in Part B. Analysis of students' answers to the Part A questions showed that not all the test items gave useful information. There was no significant difference in the students' ability to visualise the structures of those molecules represented by ball and stick formulae and those represented by dimensional formulae (see page 86). The two representations make use of different depth cues, but the component steps required to solve three-dimensional thinking problems are essentially the same for both representations. It would therefore be possible to obtain the same information from test items using ball and stick representations only. For further research, therefore, only questions on ball and stick formulae need be included. This would mean that Part A would consist of twelve items instead of twenty-four.

Similarly, not all the test items in Part B gave useful information. Analysis of students' answers showed that the items which tested the students' visualisation of depth cues after an operation of rotation (questions 17 - 24) gave no new information. The information given by these questions was essentially the same as that given by the questions which tested the use of depth cues to visualise the structures of molecules (questions 1 - 7). Questions 17 - 24 could therefore be excluded. Further research could hence be conducted using an abbreviated question paper.

7.3.2. The remedial instruction programme

Previous studies have reported instruction programmes that were effective for teaching visualisation of the depth cues, rotation about the axes and reflection in the planes. The programmes used by Oyediji (1978), Seddon, Adeola, El Farra and Oyediji (1984) and Seddon and Shubber (1985) improved students' visualisation of each cue that was taught. There was, however, no transfer of learning between different cues. In order for learning to be most effective therefore, instruction should be given on the use of each of the depth cues. In contrast, the instruction programme designed in this research emphasised as few aspects as possible. The overlap cue is sufficient, without considering any other cues, to determine unambiguously which atoms are closer to, and which atoms further away from, the viewer than the plane of the paper. The other cues are therefore not essential and the programme could be shortened by leaving out all other cues.

Previous instruction programmes have used teaching aids such as stereodiagrams and shadows in order to teach the visualisation of rotation and reflection. These programmes were reported to be effective in improving students' visualisation. In addition, they were interesting to the students and motivated them by their novelty. However, they rely on observations of rotations and reflections which can soon be confused or forgotten. No logical rules or specific instructions on the operations are given. In the absence of the stereodiagrams or shadows, students may still have the same difficulty with the visualisation of operations as they did before the programme. Such programmes do not, really, address the reasons for difficulty and therefore do not reach the root of the problem. In this study, three-dimensional thinking problems were analysed into their component steps. Competence in each of these steps and the ability to link them into a logical sequence should be sufficient for solving all problems involving three-dimensional thinking. A logical set of simple rules for solving three-dimensional visualisation problems was given to the students. These rules are easy to learn and remember.

Seddon, Tariq, and Dos Santos Veiga (1984) reported that their programme significantly improved students' visualisation of each operation of rotation and reflection that was taught, but again that there was no transfer of learning between different axes and planes. For maximum effectiveness, therefore, instruction should be given on rotation about each axis and reflection in each plane. This was done in the present remedial programme. The remedial instruction made use of inexpensive models and mirrors and focused on only four simple aspects. These aspects were: the use of the depth cues, the meaning of the words used in the questions, the ability to visualise the orientation of the axes and planes, and the positions of atoms after an operation of rotation or reflection.

7.4. Summary of the main findings of the research

The results of the pretest showed that the students tested in this research had poor spatial visualisation skills initially. Similar findings with students from other cultural groups have been reported by other researchers (Maccoby and Jacklin, 1974; McGee, 1979; Seddon et al, 1982; Seddon, Eniaiyeju and Jusoh, 1984; Seddon, Tariq and Dos Santos Veiga, 1984; Seddon and Shubber, 1984, 1985a, 1985b; Hilton, 1986). The students had difficulty in the overall task of visualising the effects of the operation of rotation on diagrams of molecules; and the difficulty was even greater for the operation of reflection. Previous studies have however failed to identify reasons for these poor visualisation skills. In this research, three-dimensional thinking problems were analysed into their component steps, and students' competence in each step was tested. The main reasons for the students' difficulties were identified from their answers. It was found that the students experienced difficulty with all the component steps that were tested. The main aspects of three-dimensional thinking that caused difficulty, as shown by the answers to the Part B questions, are given below. The percentages of students who had difficulty are given in parenthesis after each step. The aspects that caused difficulty were:

(a) the three-dimensional visualisation of the structure of a molecule, using the depth cues (35% for ball and stick formulae, 42% for dimensional formulae),
(b) the understanding of the meaning of the words used in the questions (45% for "rotation about an axis", 55% for "reflection in a plane"),
(c) the visualisation of the orientation of the axes (77%) and planes (94%),
(d) the visualisation of the positions of atoms after an operation of rotation (81%) or reflection (90%).

Although students performed poorly in the pretest, a single ninety-minute remedial instruction session was enough to improve their results very significantly ($p < 0{,}01$), as shown by an analysis of covariance (see page 116). After instruction the students' overall ability to visualise the operations of rotation and reflection improved, as did their performance on each of the aspects taught. These aspects were: the use of the depth cues, the meaning of the words used in the questions, visualisation of the orientation of the axes and planes and of the positions of atoms after an operation of rotation or reflection. The instruction on the meaning of the depth cues was sufficient to markedly improve students' ability to visualise the three-dimensional structures of molecules. About 90% of the students could visualise the structures perfectly after instruction. The results showed that students' difficulties were due to lack of understanding of some simple aspects. These difficulties can be overcome by instruction concerning these simple aspects.

The results also showed that there was no difference in visualisation skills between the men and the women who were tested.

7.5. Recommendations for the implementation of the results of this research

It is inadvisable for chemistry teachers, even at universities, to assume that their students have adequate visualisation skills. In the first year at university, it should be ensured that students know the meaning and correct use of the depth cues and can visualise the operations (such as rotation and reflection) made use of in chemistry.

Tests of three-dimensional thinking such as the ones given in this thesis (see Appendix 1), or shortened versions of these tests, can be made use of to identify students who are in need of remedial instruction. Instruction on the skills required for three-dimensional thinking could be given, as and when required, during normal chemistry lectures. Some chemistry lecturers may feel that their syllabus is too large for them to be able to spare time for teaching such skills, but this is a fallacy. Carefully designed teaching of skills would really save time in the long term, as it would often make the teaching of the content that requires the skills more effective. The short instruction programme (see Appendix 2) has been shown to be very effective in improving students' three-dimensional visualisation skills. The only teaching aids which the programme requires are mirrors and simple models. The cost involved is therefore low. The programme would thus be suitable for use even where resources are limited.

7.6. Suggestions for further research

The post-test results showed that the remedial instruction programme was more effective with respect to rotation about the X- and Y-axes than about the Z-axis. The programme could therefore be developed to devote more time to teaching rotation about the Z-axis. The results also show a need for further instruction on reflection.

The subjects in this research were students at the University of Bophuthatswana. This research could be extended to students at other universities in Southern Africa. Comparisons between the spatial visualisation skills of students from rural and urban backgrounds could be made. Students from different cultural groups could also be compared. A survey could be undertaken to investigate whether students from different cultural groups have different visualisation abilities, and whether they benefit equally from remedial instruction.

This research was limited to the operations of rotation and reflection, and to molecules represented by ball and stick and dimensional formulae. Similar studies could be undertaken for other operations (such as inversion) and for other representations, such as Newman projections and Fischer projections.

This research programme concentrated on students at university level. Simplified tests and remedial instruction could be conducted for school pupils. The visualisation of operations may be more appropriate for university students, but instruction on depth cues could be given at school. The earlier that the required three-dimensional visualisation skills are developed, the better.

It has been suggested (Baker and Talley, 1974; Hyman, 1982; Small and Morton, 1983; Pribyl and Bodner, 1985; Carter et al, 1987; Rochford, 1987a) that there is a correlation between spatial visualisation skills and success in chemistry. Research could be undertaken to investigate the correlation between students' scores on tests of three-dimensional visualisation and tests of chemistry content. This could be done both before and after the students have undergone remedial instruction.

7.7. Conclusion

This research differs from previous studies in that it identifies reasons for the students' difficulties in three-dimensional thinking. The instruction programme was designed after the aspects which caused difficulty had been identified from the students' answers to the test items. Each standard three-dimensional problem was analysed into a few simple steps. Instruction was given on each of these steps. The steps are logical and a set of rules was given which can easily be understood and learned. The results of the post-test showed that the programme was extremely effective ($p < 0{,}01$) in improving students' three-dimensional thinking.

APPENDIX 1

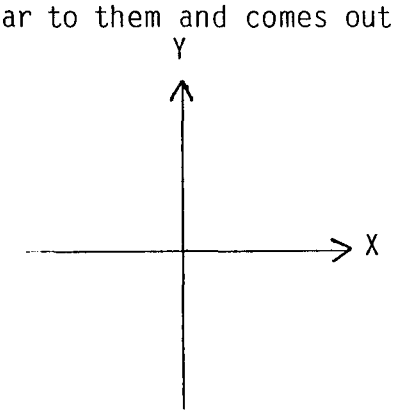
THE TESTS OF THREE-DIMENSIONAL VISUALISATION

PRETEST - PART A

This question paper tests your understanding of diagrams of three-dimensional molecules.

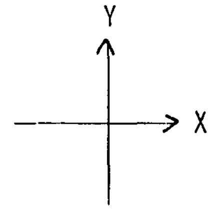
a) The molecules consist of a central atom, atom A, which is bonded to a number of other atoms.
b) Atom A is in the plane of the paper, in each case.
c) All the bond lengths are equal, in each molecule.

Note that the X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.

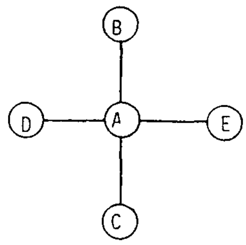


Write your answers on the answer sheet provided. Do not write on the question paper. Attempt to answer all the questions.

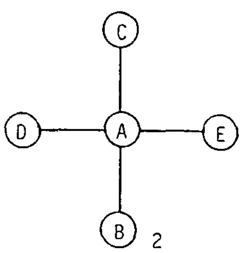
Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



1. Consider the square planar molecule represented in diagram 1 below:

1 

Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Y-axis?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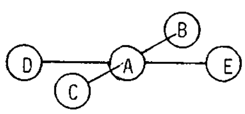
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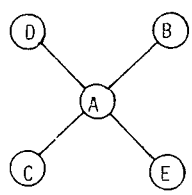
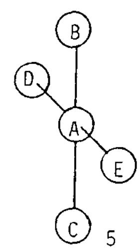
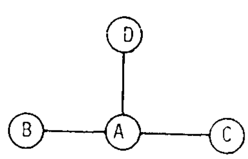
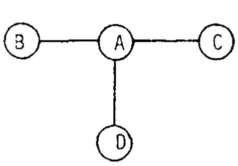

4

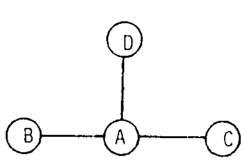

5

2. Consider the T-shaped molecule represented in diagram 1 below:

1 

Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XY plane?


2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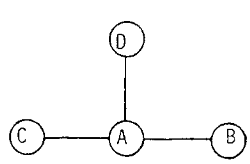
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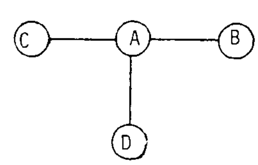
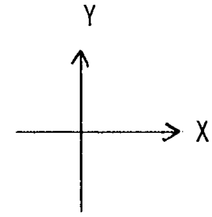
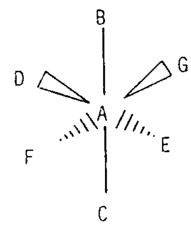

5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

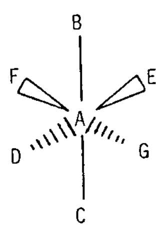


3. Consider the octahedral molecule represented in diagram 1 below:

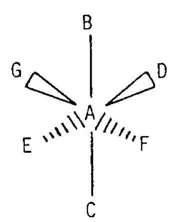
1



Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XZ plane?



2



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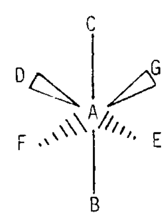

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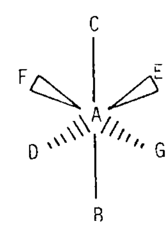
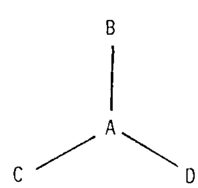


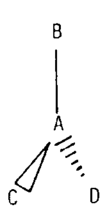
5

4. Consider the trigonal planar molecule represented in diagram 1 below:

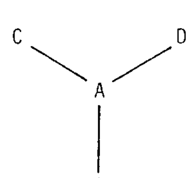
1



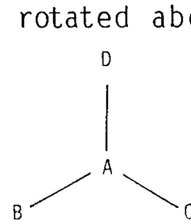
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Z-axis?



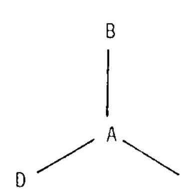
2



3

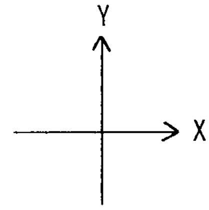


4



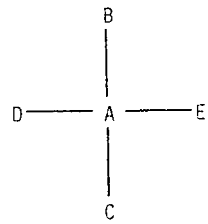
5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

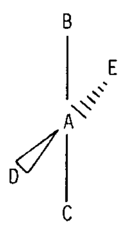


5. Consider the square planar molecule represented in diagram 1 below:

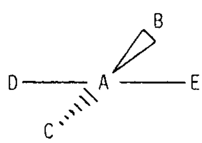
1



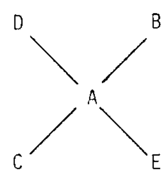
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could lock like if it were rotated about the X-axis?



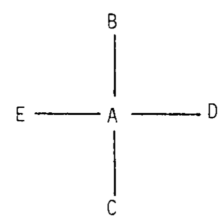
2



3



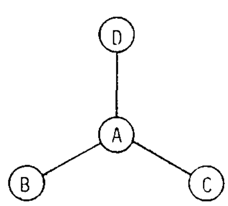
4



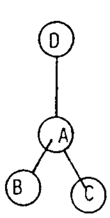
5

6. Consider the trigonal planar molecule represented in diagram 1 below:

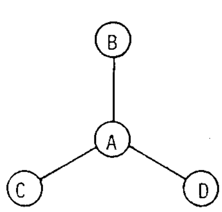
1



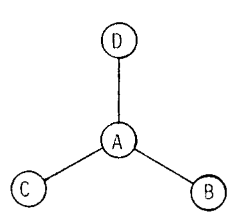
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the X-axis?



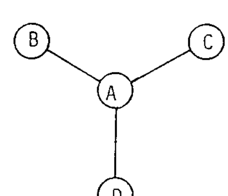
2



3

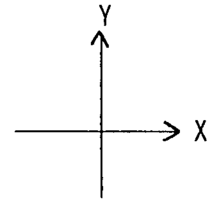


4



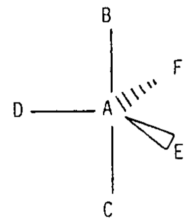
5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

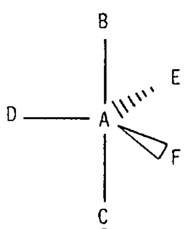


7. Consider the trigonal bipyramidal molecule represented in diagram 1 below:

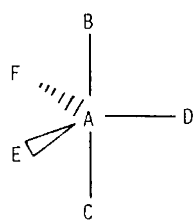
1



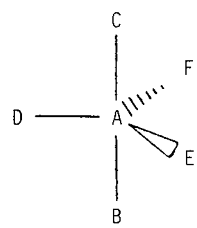
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XY plane?



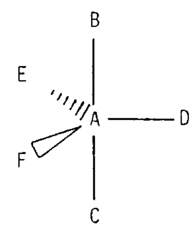
2



3



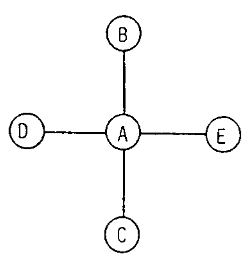
4



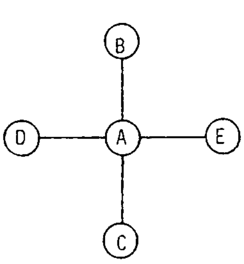
5

8. Consider the square planar molecule represented in diagram 1 below:

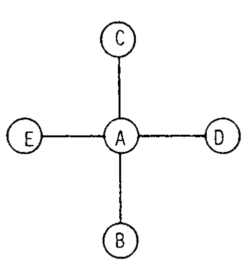
1



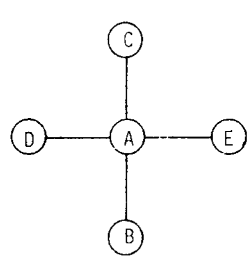
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the YZ plane?



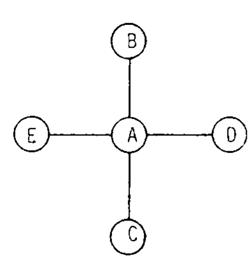
2



3

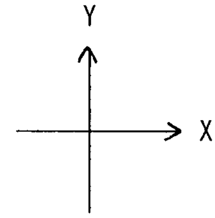


4



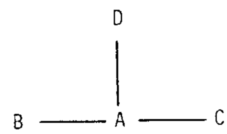
5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

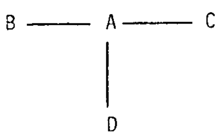


9. Consider the T-shaped molecule represented in diagram 1 below:

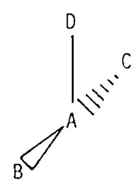
1



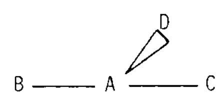
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Y-axis?



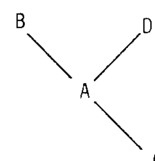
2



3



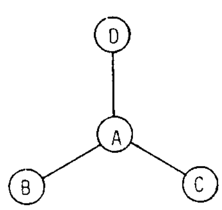
4



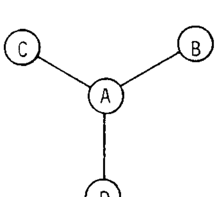
5

10. Consider the trigonal planar molecule represented in diagram 1 below:

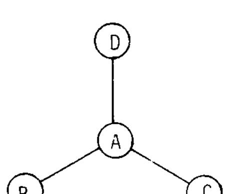
1



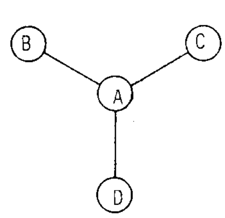
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XZ plane?



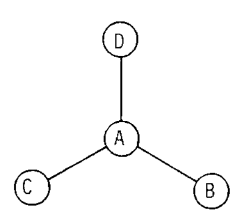
2



3

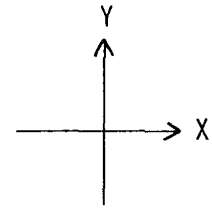


4



5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



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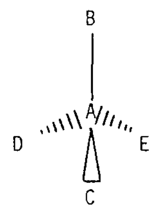
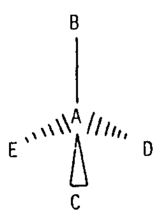
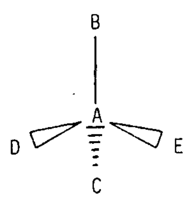
11. Consider the tetrahedral molecule represented in diagram 1 below:

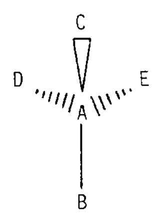
1

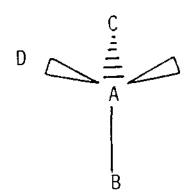


Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the YZ plane?


2

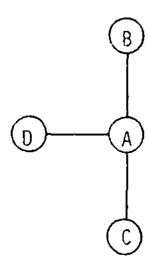

3


4

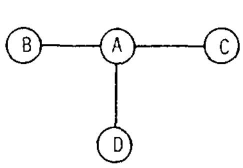

5

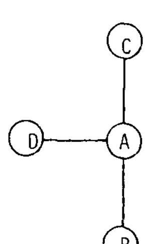
12. Consider the T-shaped molecule represented in diagram 1 below:

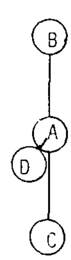
1

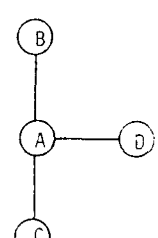


Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Z-axis?

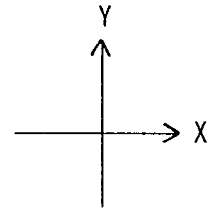

2


3


4

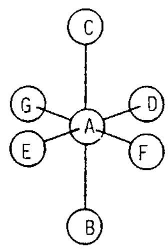

5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

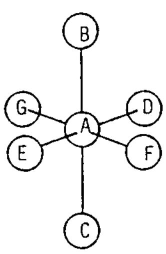


13. Consider the octahedral molecule represented in diagram 1 below:

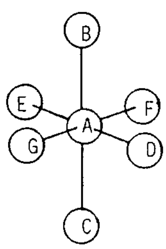
1



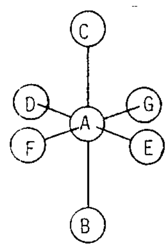
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the YZ plane?



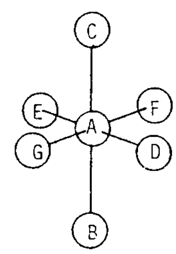
2



3



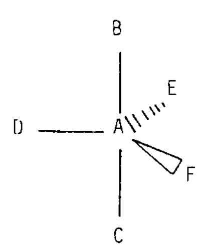
4



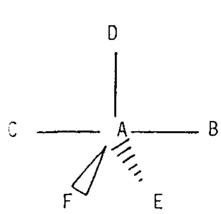
5

14. Consider the trigonal bipyramidal molecule represented in diagram 1 below:

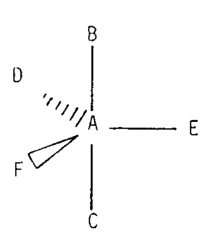
1



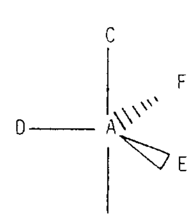
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Y-axis?



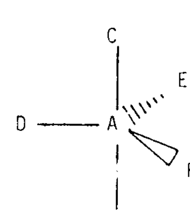
2



3

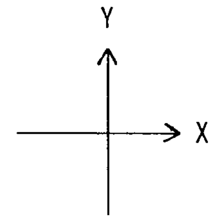


4

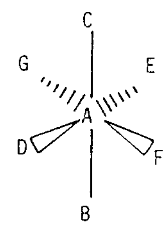


5

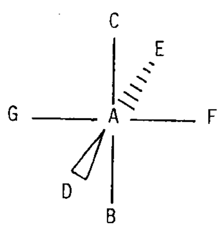
Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



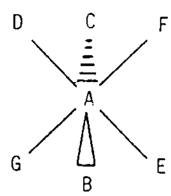
15. Consider the octahedral molecule represented in diagram 1 below:

1


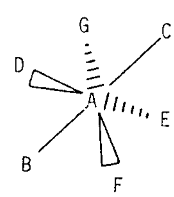
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Z-axis?



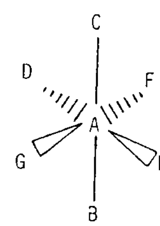
2



3

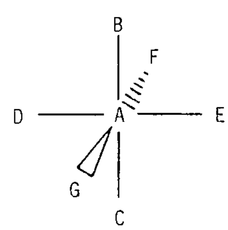


4

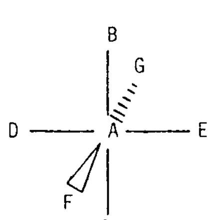


5

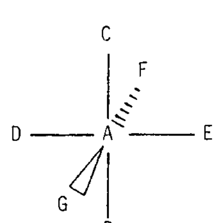
16. Consider the octahedral molecule represented in diagram 1 below:

1


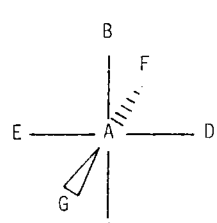
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XY plane?



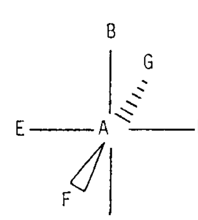
2



3

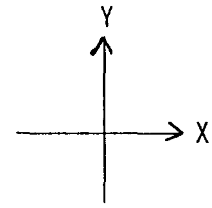


4



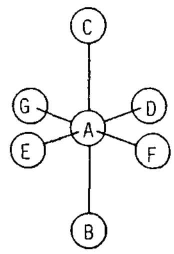
5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

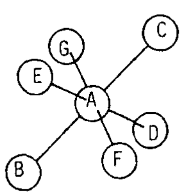


17. Consider the octahedral molecule represented in diagram 1 below:

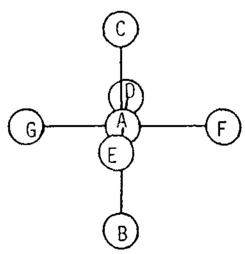
1



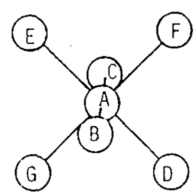
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Y-axis?



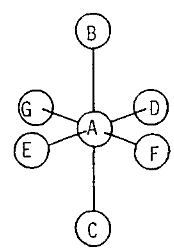
2



3



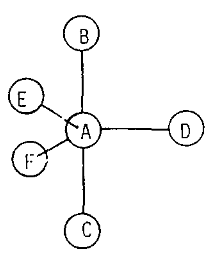
4



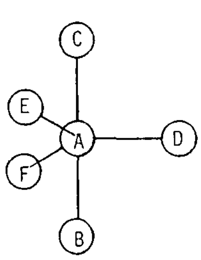
5

18. Consider the trigonal bipyramidal molecule represented in diagram 1 below:

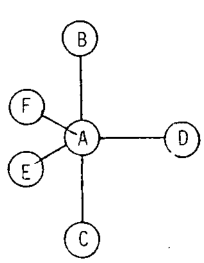
1



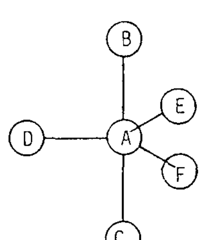
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XZ plane?



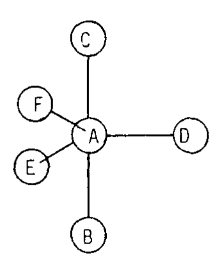
2



3

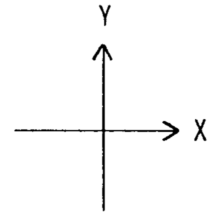


4



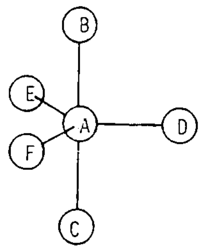
5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

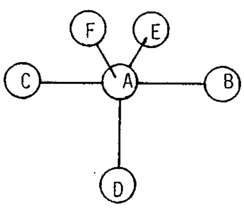


19. Consider the trigonal bipyramidal molecule represented in diagram 1 below:

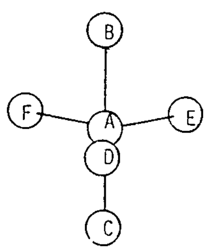
1



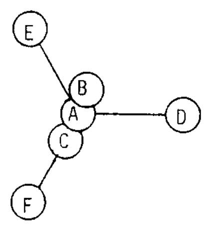
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the X-axis?



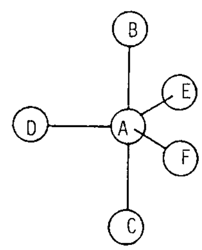
2



3



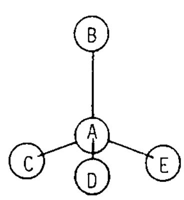
4



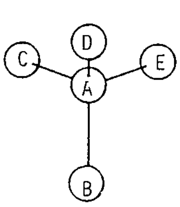
5

20. Consider the tetrahedral molecule represented in diagram 1 below:

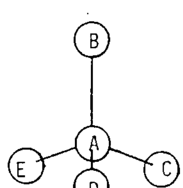
1



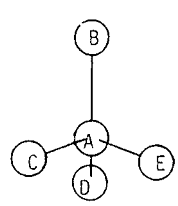
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XY plane?



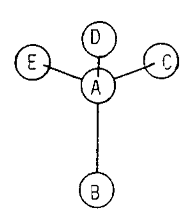
2



3

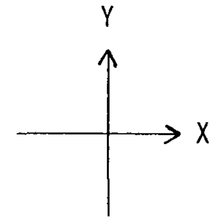


4

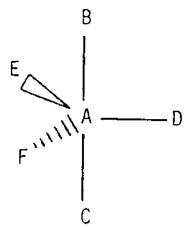


5

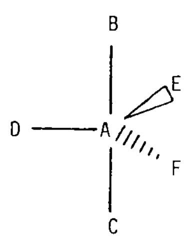
Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



21. Consider the trigonal bipyramidal molecule represented in diagram 1 below:

1 

Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the YZ plane?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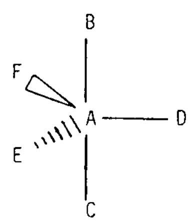
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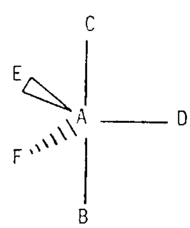
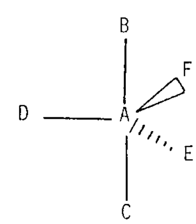
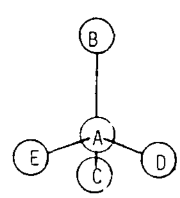
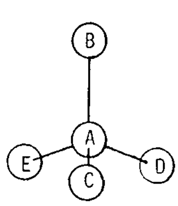

4


5

22. Consider the tetrahedral molecule represented in diagram 1 below:

1 

Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Z-axis?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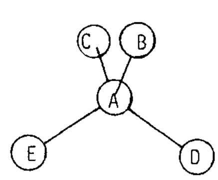
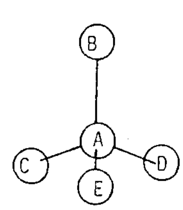
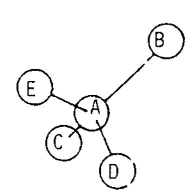
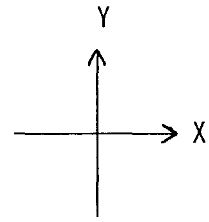

3


4

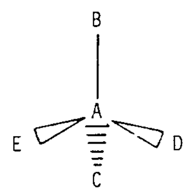

5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

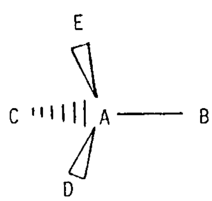


23. Consider the tetrahedral molecule represented in diagram 1 below:

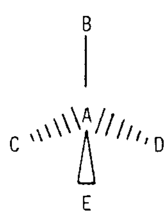
1



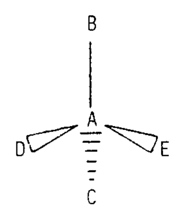
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the X-axis?



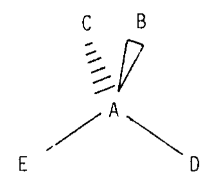
2



3



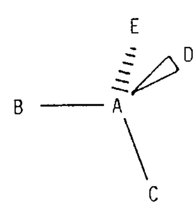
4



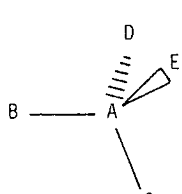
5

24. Consider the tetrahedral molecule represented in diagram 1 below:

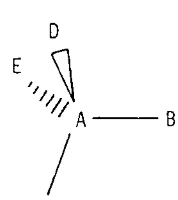
1



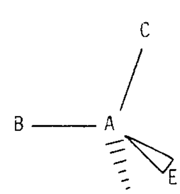
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XZ plane?



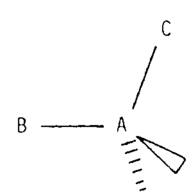
2



3



4



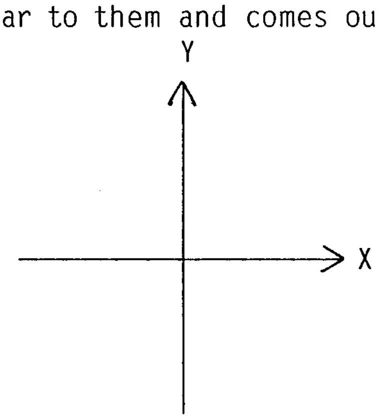
5

PRETEST - PART B

This question paper tests your understanding of diagrams of three-dimensional molecules.

a) The molecules consist of a central atom, Atom A, which is bonded to a number of other atoms.
b) Atom A is in the plane of the paper, in each case.
c) All the bond lengths are equal, in each molecule, except in Question 1.

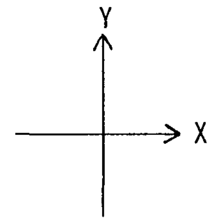
Note that the X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.



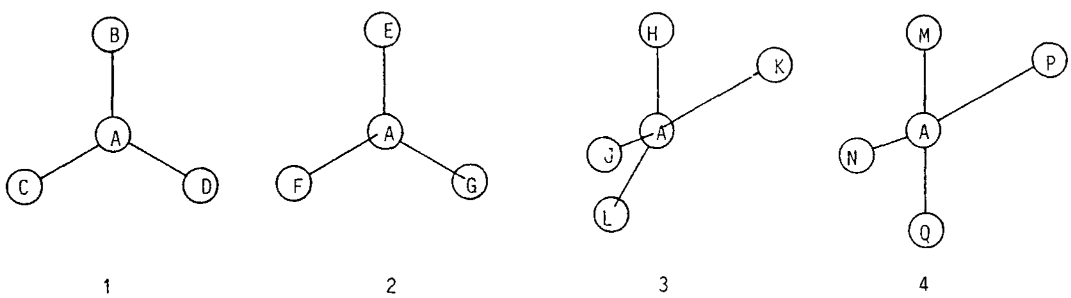
Write your answers on the paper provided. Do not write on the question paper. Attempt to answer <u>all</u> the questions, and answer them in the order in which they are given in this question paper.

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.

b) Atom A is in the plane of the paper.



1. Consider the hypothetical molecules (1, 2, 3 and 4) represented below: (The bond lengths may not be equal.)



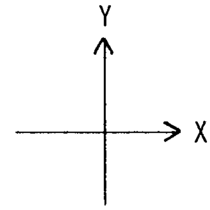
i) In which of the molecules are all the atoms in the plane of the paper?

ii) Which of the atoms are closer to you than the plane of the paper?

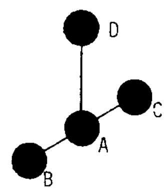
iii) Which of the atoms are further away from you than the plane of the paper?

State, in each case, which clue(s) in the diagrams helped you to come to your conclusion.

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

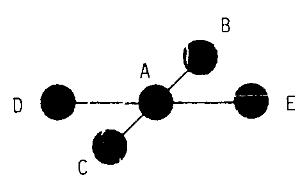


2. Consider the symmetrical T-shaped molecule represented below:



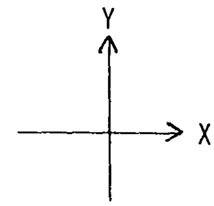
i) Which (if any) of the atoms B, C and D are not in the plane of the paper?
ii) Draw a diagram to show what this molecule would look like if all the atoms were in the plane of the paper.

3. Consider the symmetrical square planar molecule represented below:

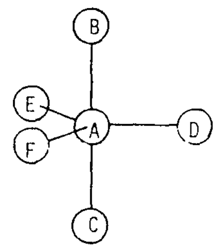


i) Which (if any) of the atoms B, C, D and E are not in the plane of the paper?
State which clue(s) in the diagram helped you to come to your conclusion.
ii) Draw a diagram to show what this molecule would look like if all the atoms were in the plane of the paper.

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

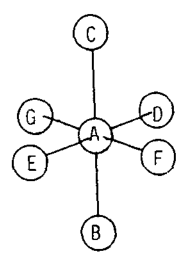


4. Consider the molecule represented below:



i) Which (if any) of the atoms B, C, D, E and F are not in the plane of the paper?
ii) Which (if any) of the atoms are closer to you than the plane of the paper?
iii) Which (if any) of the atoms are further away from you than the plane of the paper?

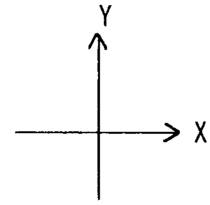
5. Consider the molecule represented below:



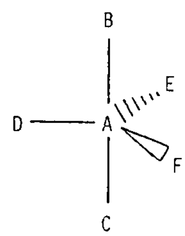
i) Which (if any) of the atoms B, C, D, E, F and G are not in the plane of the paper?
ii) Which (if any) of the atoms are closer to you than the plane of the paper?
iii) Which (if any) of the atoms are further away from you than the plane of the paper?

State which clue(s) in the diagram helped you to come to your conclusion.

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

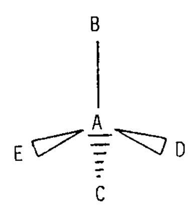


6. Consider the molecule represented below:



i) Which (if any) of the atoms B, C, D, E and F are not in the plane of the paper?
ii) Which (if any) of the atoms are closer to you than the plane of the paper?
iii) Which (if any) of the atoms are further away from you than the plane of the paper?

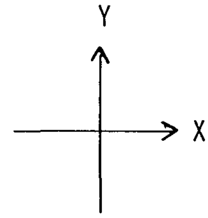
7. Consider the molecule represented below:



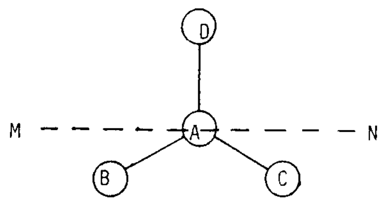
i) Which (if any) of the atoms B, C, D and E are not in the plane of the paper?
ii) Which (if any) of the atoms are closer to you than the plane of the paper?
iii) Which (if any) of the atoms are further away from you than the plane of the paper?

State which clue(s) in the diagram helped you to come to your conclusion.

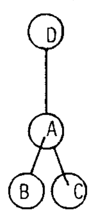
Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



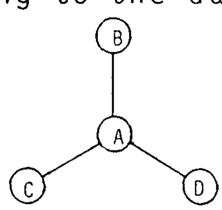
8. Consider the trigonal planar molecule represented in diagram 1 below:

1 

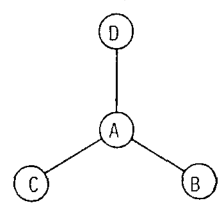
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if you turned it around the axis corresponding to the dashed line MN?



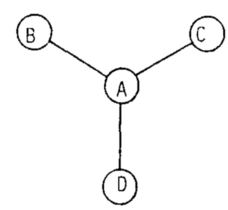
2



3

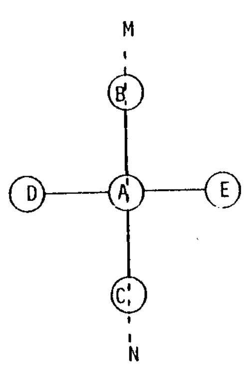


4

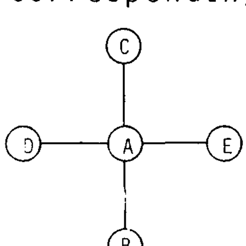


5

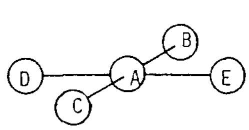
9. Consider the square planar molecule represented in diagram 1 below:

1 

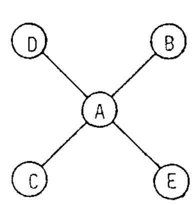
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if you turned it around the axis corresponding to the dashed line MN?



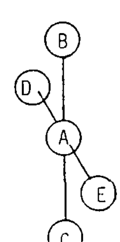
2



3

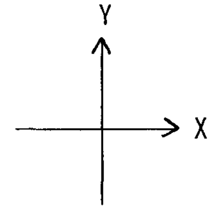


4



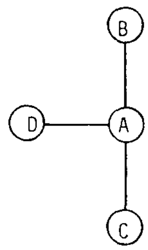
5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

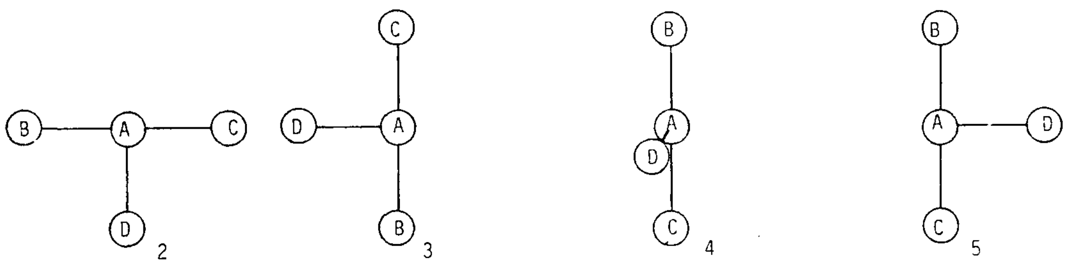


10. Consider the T-shaped molecule represented in diagram 1 below:

1

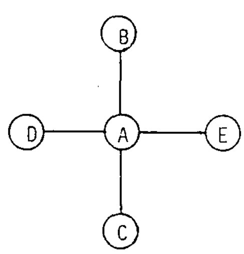


Imagine a line through Atom A coming straight out of the plane of the paper. Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if you turned it around the line?



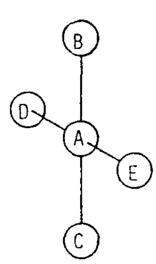
11. Consider the square planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1

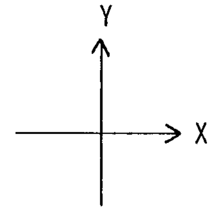


About which axis (X, Y or Z) must the molecule be rotated if it is to look like diagram 2?

2



Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



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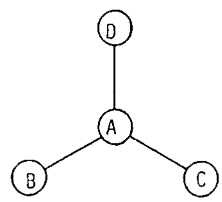
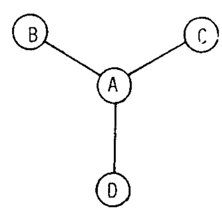
12. Consider the trigonal planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1



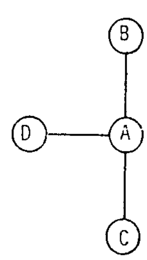
About which axis (X, Y or Z) must the molecule be rotated if it is to look like diagram 2?

2



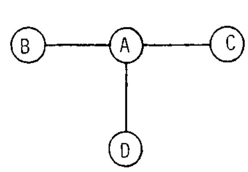
13. Consider the T-shaped molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1

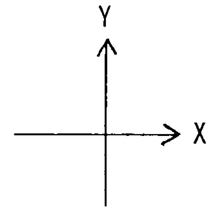


About which axis (X, Y or Z) must the molecule be rotated if it is to look like diagram 2?

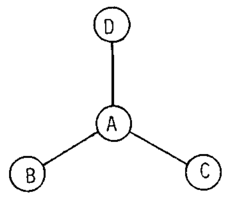
2



Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

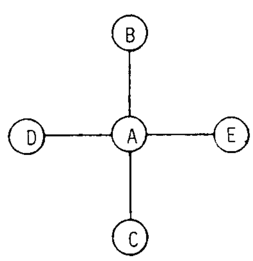


14. Consider the trigonal planar molecule represented below, in which all the atoms are in the plane of the paper:



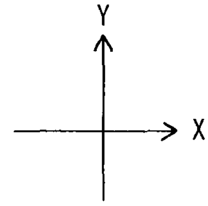
Which (if any) of the atoms A, B, C and D might not be in the plane of the paper if the molecule were rotated about the X-axis?

15. Consider the square planar molecule represented below, in which all the atoms are in the plane of the paper:

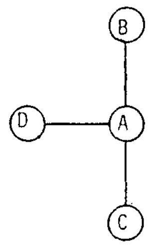


Which (if any) of the atoms A, B, C, D and E might not be in the plane of the paper if the molecule were rotated about the Y-axis?

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

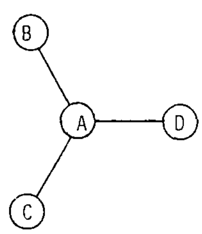


16. Consider the T-shaped molecule represented below, in which all the atoms are in the plane of the paper:

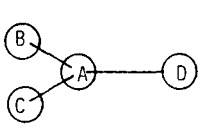


Which (if any) of the atoms A, B, C and D might not be in the plane of the paper if the molecule were rotated about the Z-axis?

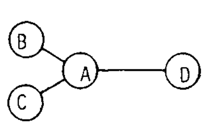
17. Consider the trigonal planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1


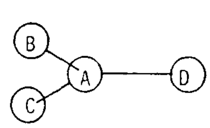
Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the X-axis? State briefly how you came to your conclusion.



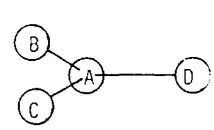
2



3

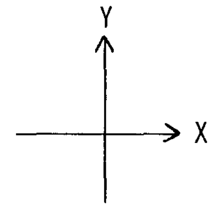


4

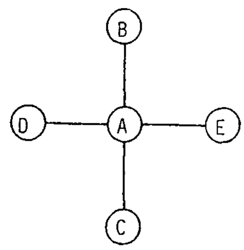


5

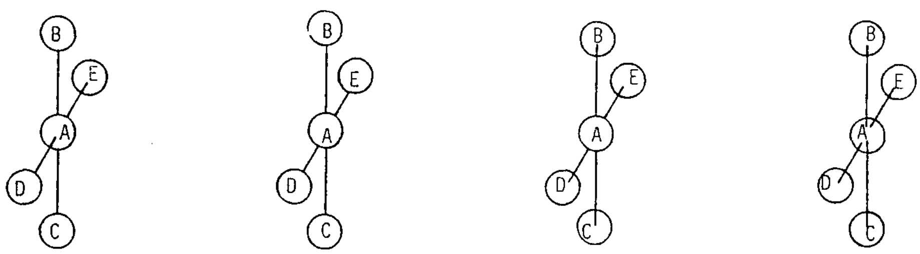
Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



18. Consider the square planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

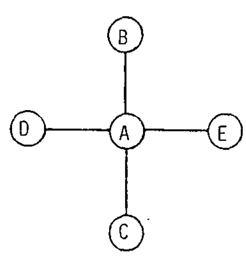
1 

Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the Y-axis? State briefly how you came to your conclusion.

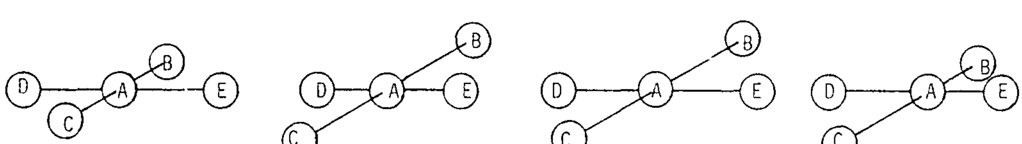


2 3 4 5

19. Consider the square planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

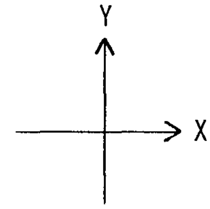
1 

Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the X-axis? State briefly how you came to your conclusion.



2 3 4 5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



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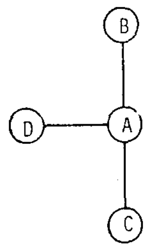
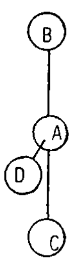
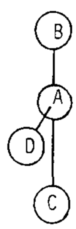
20. Consider the T-shaped molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1 

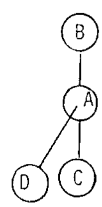
Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the Y-axis? State briefly how you came to your conclusion.



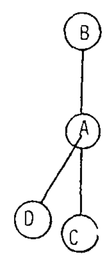
2



3

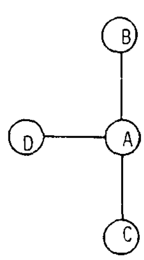


4

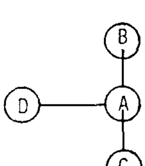


5

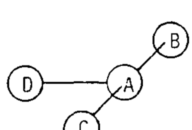
21. Consider the T-shaped molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1 

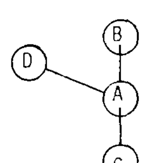
Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the X-axis? State briefly how you came to your conclusion.



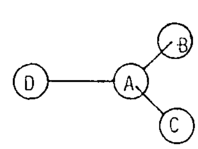
2



3

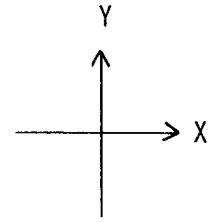


4

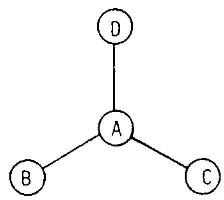


5

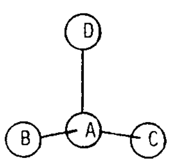
Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



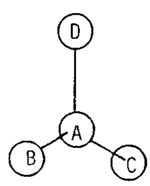
22. Consider the trigonal planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1 

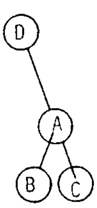
Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the Y-axis? State briefly how you came to your conclusion.



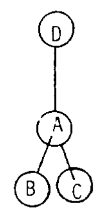
2



3

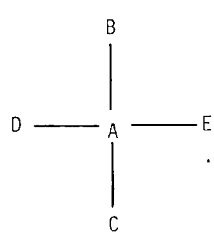


4

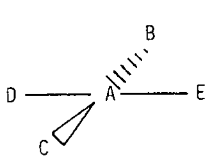


5

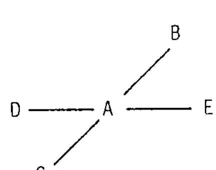
23. Consider the square planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1 

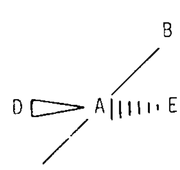
Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the X-axis?



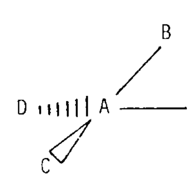
2



3

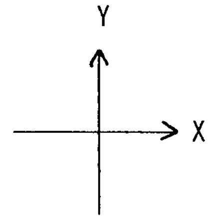


4



5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



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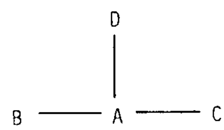
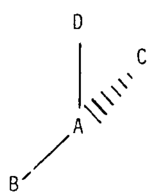
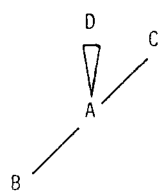
24. Consider the T-shaped molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1 

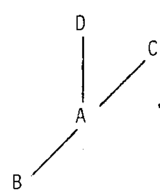
Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the Y-axis?



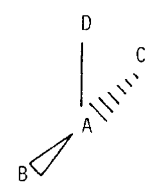
2



3

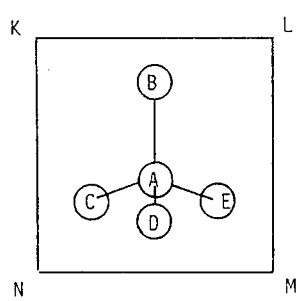


4

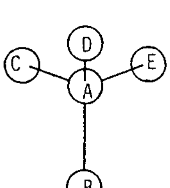


5

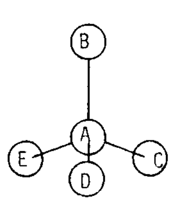
25. A square shaped mirror (KLMN) is placed behind a tetrahedral molecule as shown in diagram 1 below:

1 

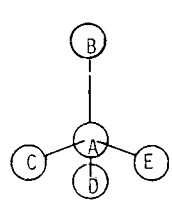
Which one of the diagrams (2, 3, 4 or 5) shows what the mirror image of the molecule would look like?



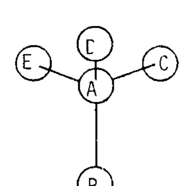
2



3

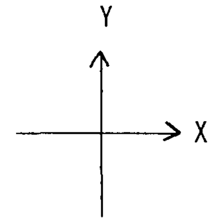


4

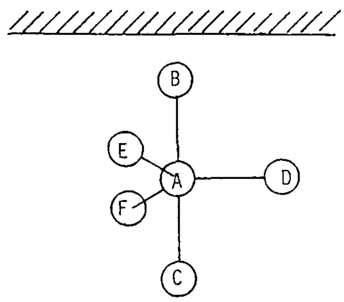


5

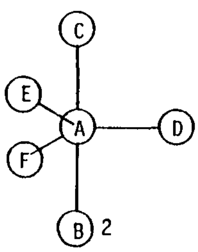
Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



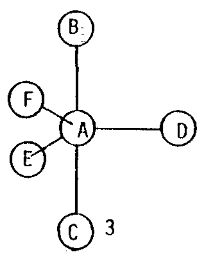
26. A mirror is in a plane perpendicular to the plane of the paper and a trigonal bipyramidal molecule is placed below the mirror as shown in diagram 1 below:

1


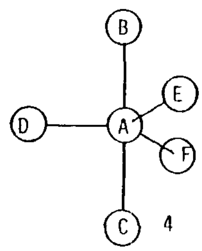
Which one of the diagrams (2, 3, 4 or 5) shows what the mirror image of the molecule would look like?



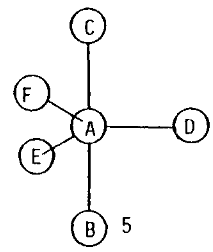
2



3

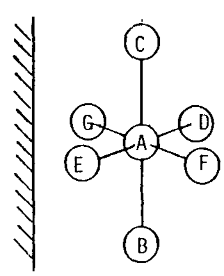


4

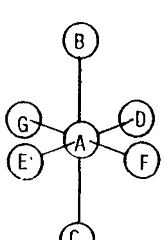


5

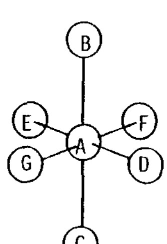
27. A mirror perpendicular to the plane of the paper is placed to the left of an octahedral molecule as shown in diagram 1 below:

1


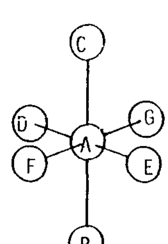
Which one of the diagrams (2, 3, 4 or 5) shows what the mirror image of the molecule would look like?



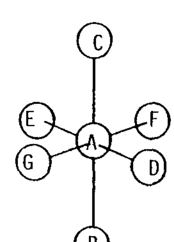
2



3

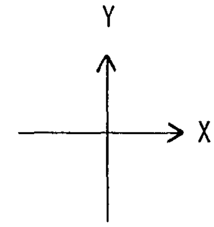


4



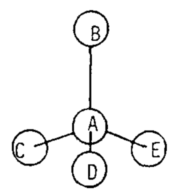
5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



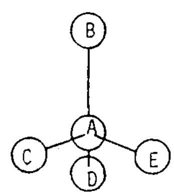
28. Consider the tetrahedral molecule represented in diagram 1 below. Atoms A and B are in the plane of the paper, atoms C and E are further away from you than the plane of the paper and atom D is closer to you than the plane of the paper.

1



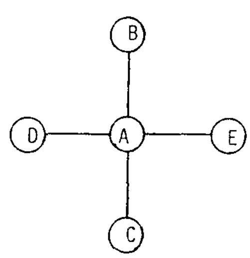
In which plane (XY, XZ or YZ) must the molecule be reflected if it is to look like diagram 2?

2



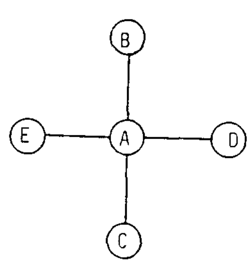
29. Consider the square planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1

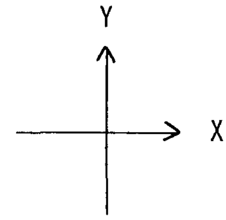


In which plane (XY, XZ or YZ) must the molecule be reflected if it is to look like diagram 2?

2

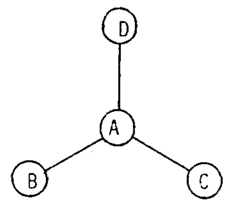


Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



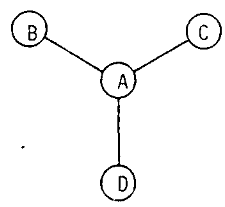
30. Consider the trigonal planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1

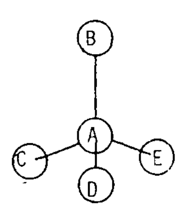


In which plane (XY, XZ or YZ) must the molecule be reflected if it is to look like diagram 2?

2

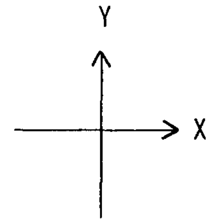


31. Consider the molecule represented below. Atoms A and B are in the plane of the paper, atoms C and E are further away from you than the plane of the paper and atom D is closer to you than the plane of the paper:

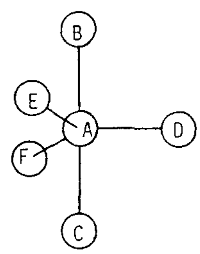


Which (if any) of the atoms would be closer to you than the plane of the paper if the molecule were reflected in the XY plane?

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

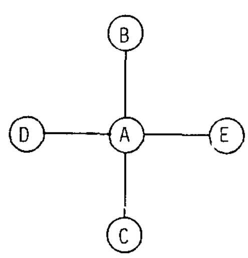


32. Consider the molecule represented below. Atoms A, B, C and D are in the plane of the paper, atom F is further away from you than the plane of the paper and atom E is closer to you than the plane of the paper:



Which atom would be closest to the top of the page if the molecule were reflected in the XZ plane?

33. Consider the molecule represented below, in which all the atoms are in the plane of the paper:



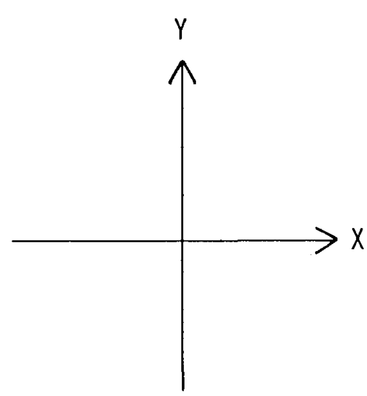
Which atom would be closest to the left hand side of the page if the molecule were reflected in the YZ plane?

POST-TEST - PART A

This question paper tests your understanding of diagrams of three-dimensional molecules.

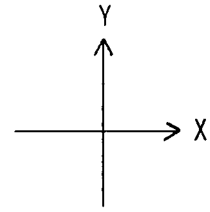
a) The molecules consist of a central atom, Atom A, which is bonded to a number of other atoms.
b) Atom A is in the plane of the paper, in each case.
c) All the bond lengths are equal, in each molecule.

Note that the X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.



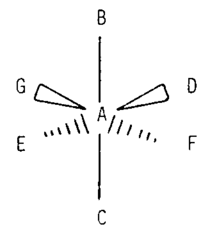
Write your answers on the answer sheet provided. Do not write on the question paper. Attempt to answer all the questions.

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

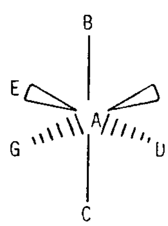


1. Consider the octahedral molecule represented in diagram 1 below:

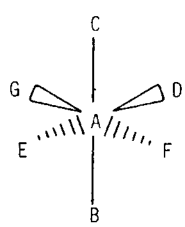
1



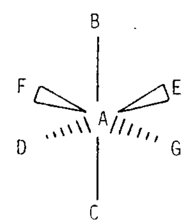
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the YZ plane?



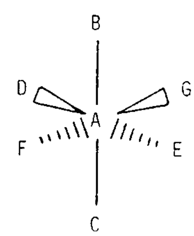
2



3



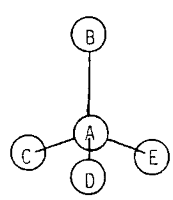
4



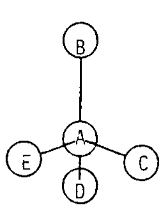
5

2. Consider the tetrahedral molecule represented in diagram 1 below:

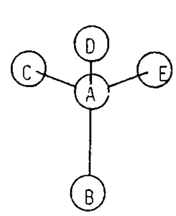
1



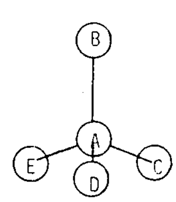
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XZ plane?



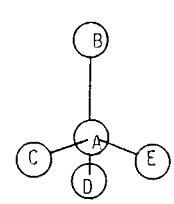
2



3

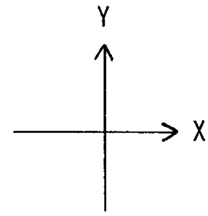


4



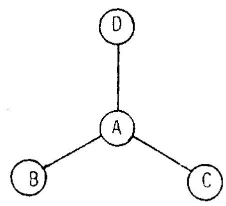
5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

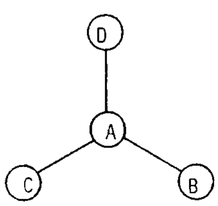


3. Consider the trigonal planar molecule represented in diagram 1 below:

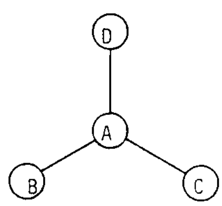
1



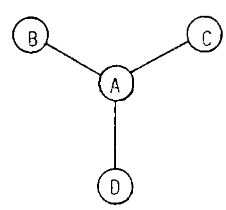
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the YZ plane?



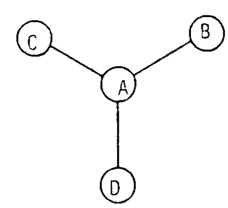
2



3



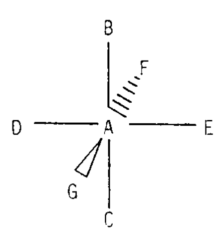
4



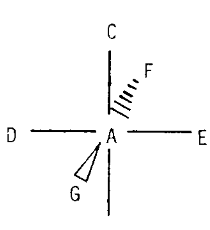
5

4. Consider the octahedral molecule represented in diagram 1 below:

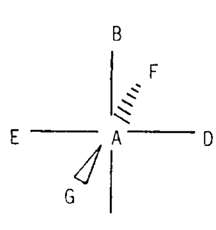
1



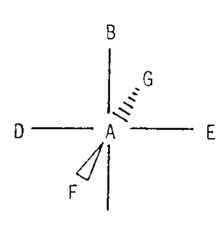
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XZ plane?



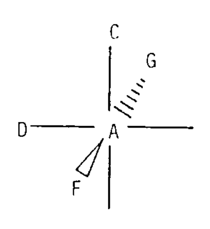
2



3

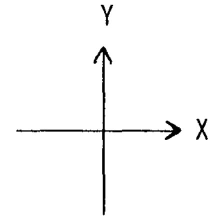


4

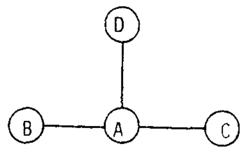


5

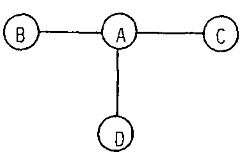
Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

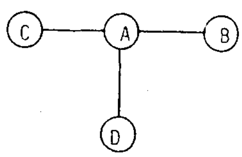


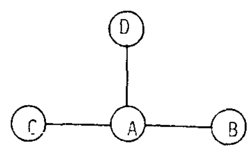
5. Consider the T-shaped molecule represented in diagram 1 below:

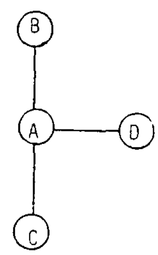
1 

Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Y-axis?

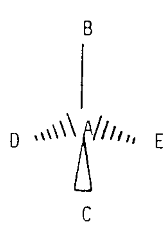

2


3

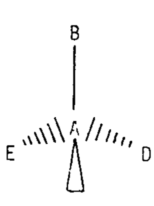

4

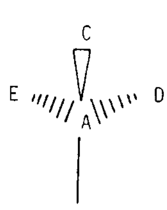

5

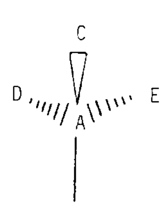
6. Consider the tetrahedral molecule represented in diagram 1 below:

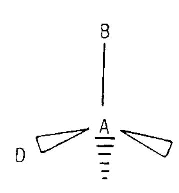
1 

Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XY plane?

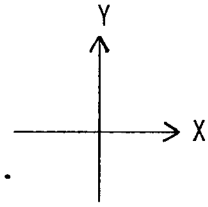

2


3


4

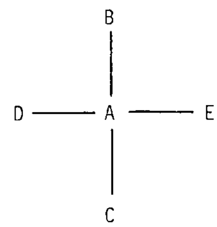

5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

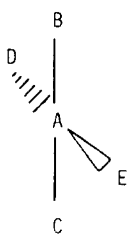


7. Consider the square planar molecule represented in diagram 1 below:

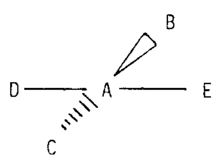
1



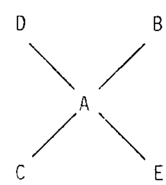
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Y-axis?



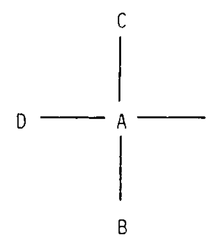
2



3



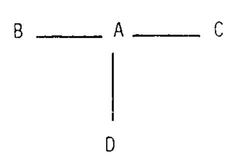
4



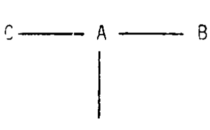
5

8. Consider the T-shaped molecule represented in diagram 1 below:

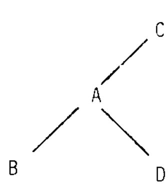
1



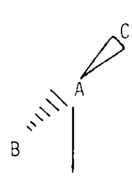
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Z-axis?



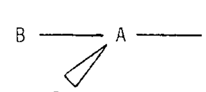
2



3

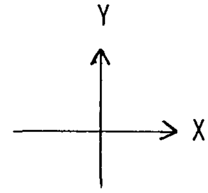


4



5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



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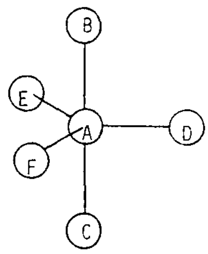
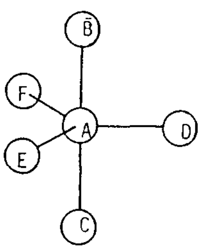
9. Consider the trigonal bipyramidal molecule represented in diagram 1 below:

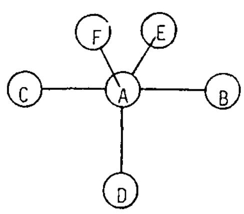
1



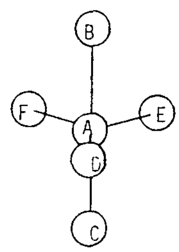
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Z-axis?



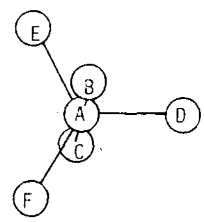
2



3



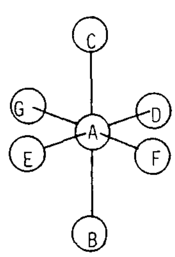
4



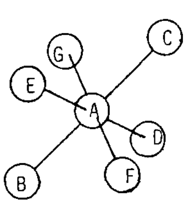
5

10. Consider the octahedral molecule represented in diagram 1 below:

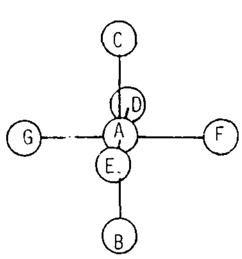
1



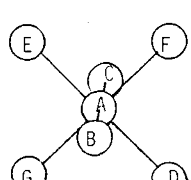
Which one of the diagrams (2, 3, 4, or 5) shows what the molecule could look like if it were rotated about the X-axis?



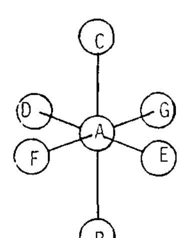
2



3

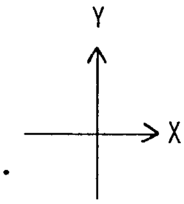


4



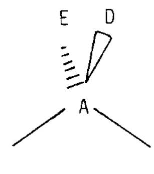
5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

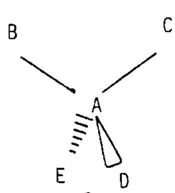


11. Consider the tetrahedral molecule represented in diagram 1 below:

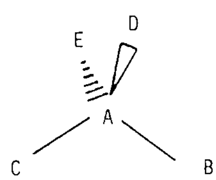
1



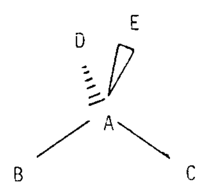
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the YZ plane?



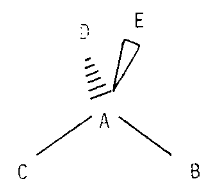
2



3



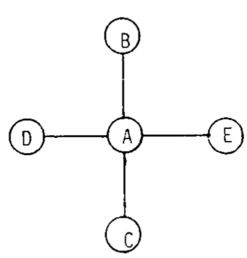
4



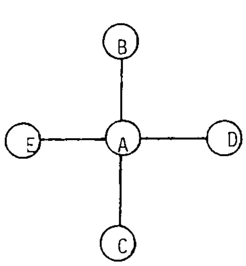
5

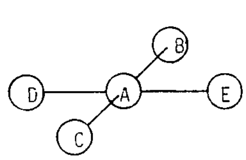
12. Consider the square planar molecule represented in diagram 1 below:

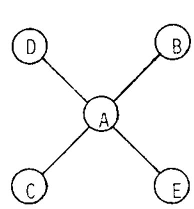
1

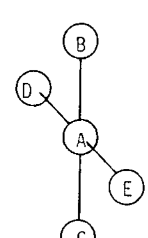


Which one of the diagrams (2, 3, 4, or 5) shows what the molecule could look like if it were rotated about the X-axis?









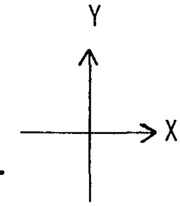
2

3

4

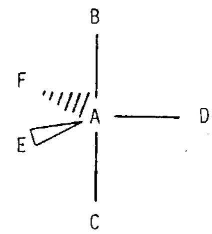
5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

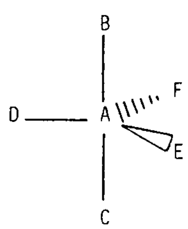


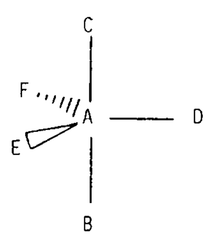
13. Consider the trigonal bipyramidal molecule represented in diagram 1 below:

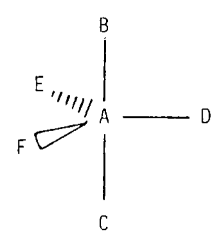
1

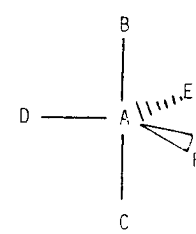


Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XY plane?





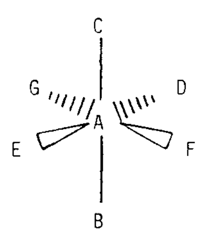




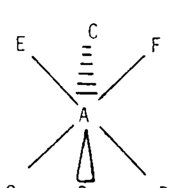
2 3 4 5

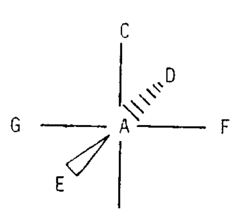
14. Consider the octahedral molecule represented in diagram 1 below:

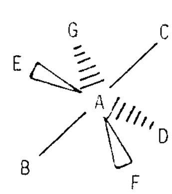
1

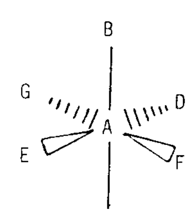


Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Y-axis?







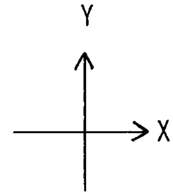


2 3 4 5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.

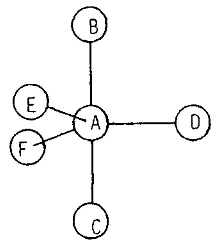
b) Atom A is in the plane of the paper.

c) All the bond lengths are equal.

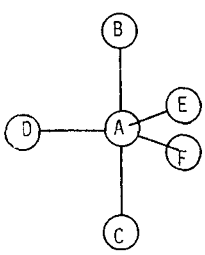


15. Consider the trigonal bipyramidal molecule represented in diagram 1 below:

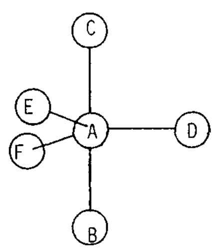
1



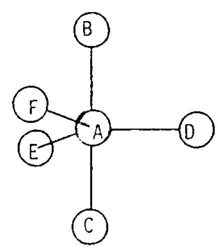
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the YZ plane?



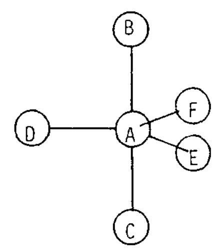
2



3



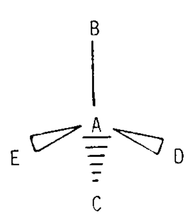
4



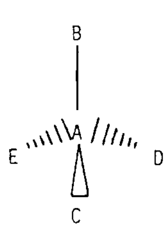
5

16. Consider the tetrahedral molecule represented in diagram 1 below:

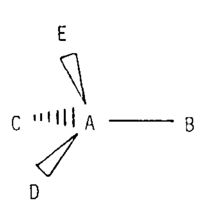
1



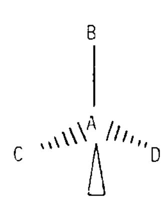
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Z-axis?



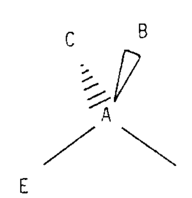
2



3



4

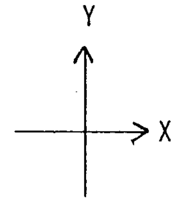


5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.

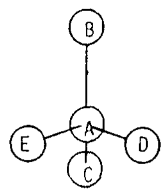
b) Atom A is in the plane of the paper.

c) All the bond lengths are equal.

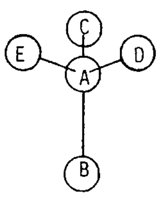


17. Consider the tetrahedral molecule represented in diagram 1 below:

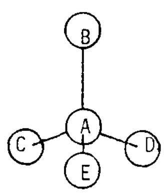
1



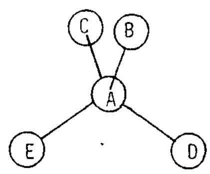
Which one of the diagrams (2, 3, 4, or 5) shows what the molecule could look like if it were rotated about the Y-axis?



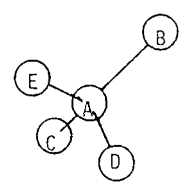
2



3



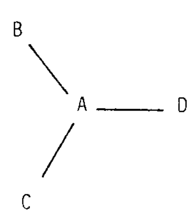
4



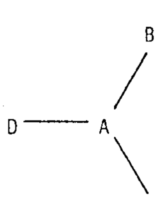
5

18. Consider the trigonal planar molecule represented in diagram 1 below:

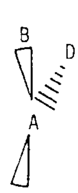
1



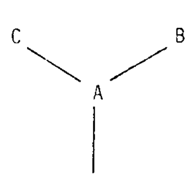
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the X-axis?



2



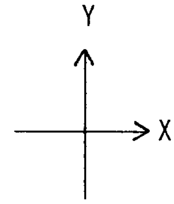
3



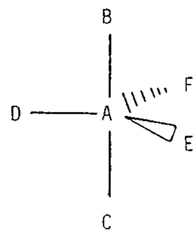
4

5

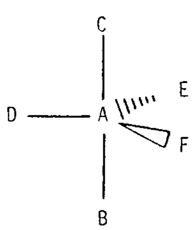
Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



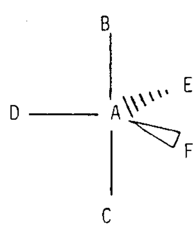
19. Consider the trigonal bipyramidal molecule represented in diagram 1 below:

1


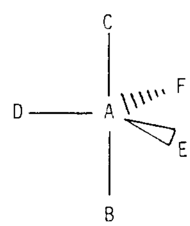
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XZ plane?



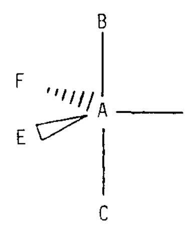
2



3

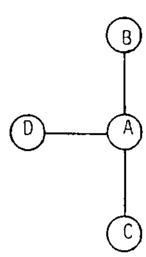


4

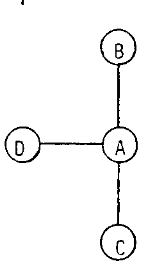


5

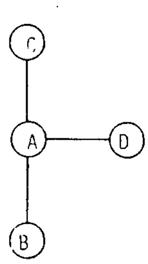
20. Consider the T-shaped molecule represented in diagram 1 below:

1


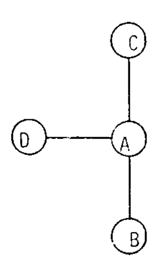
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XZ plane?



2



3



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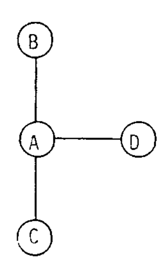
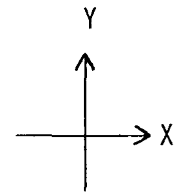
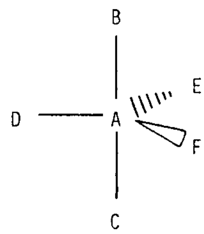


5

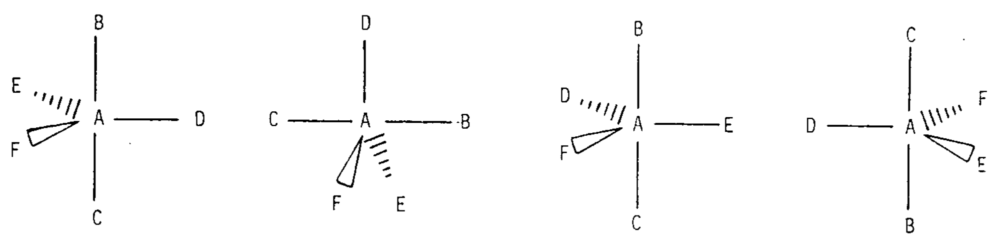
Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



21. Consider the trigonal bipyramidal molecule represented in diagram 1 below:

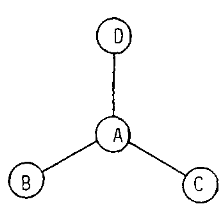
1 

Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the X-axis?

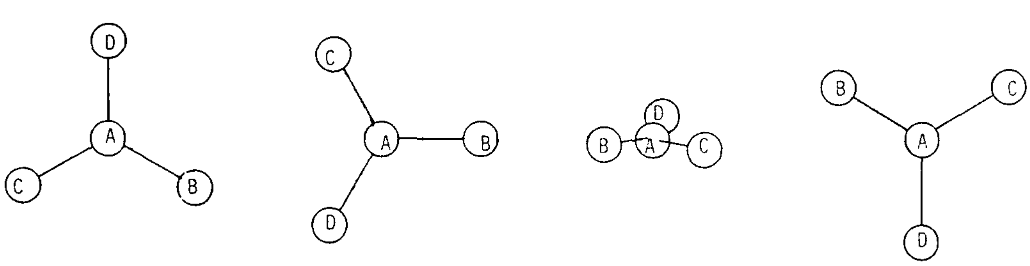


2 3 4 5

22. Consider the trigonal planar molecule represented in diagram 1 below:

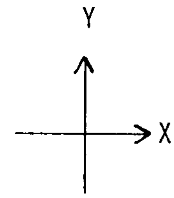
1 

Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Z-axis?



2 3 4 5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



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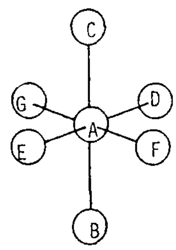
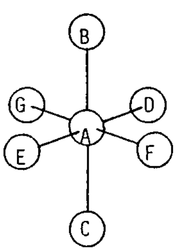
23. Consider the octahedral molecule represented in diagram 1 below:

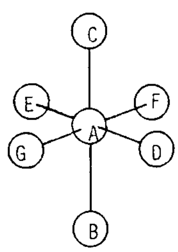
1



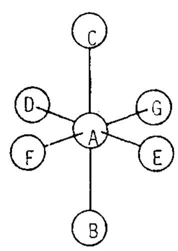
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XY plane?



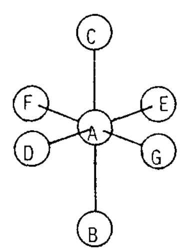
2



3



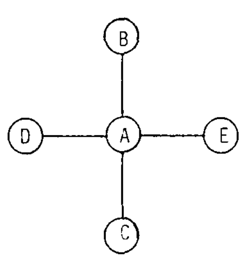
4



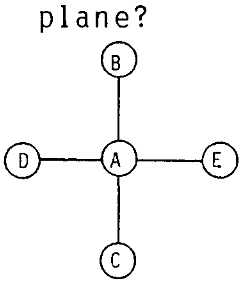
5

24. Consider the square planar molecule represented in diagram 1 below:

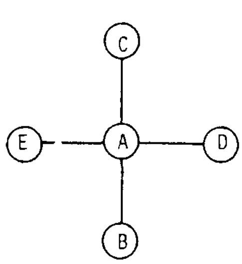
1



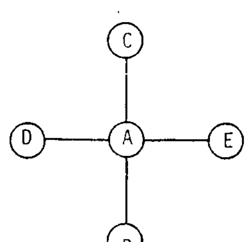
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XY plane?



2



3



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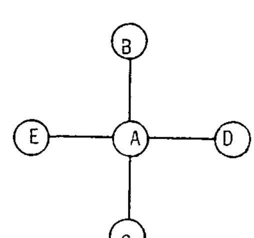


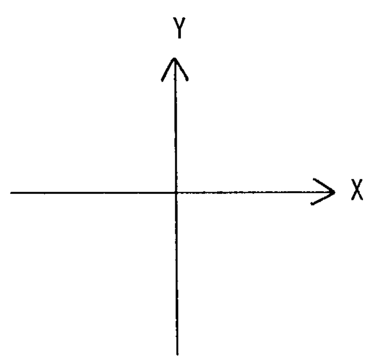
5

POST-TEST - PART B

This question paper tests your understanding of diagrams of three-dimensional molecules.

a) The molecules consist of a central atom, Atom A, which is bonded to a number of other atoms.
b) Atom A is in the plane of the paper, in each case.
c) All the bond lengths are equal, in each molecule, except in Question 1.

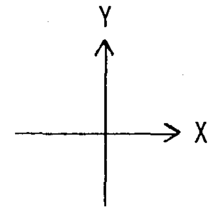
Note that the X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.



Write your answers on the paper provided. Do not write on the question paper. Attempt to answer all the questions, and answer them in the order in which they are given in this question paper.

Remember a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.

b) Atom A is in the plane of the paper.



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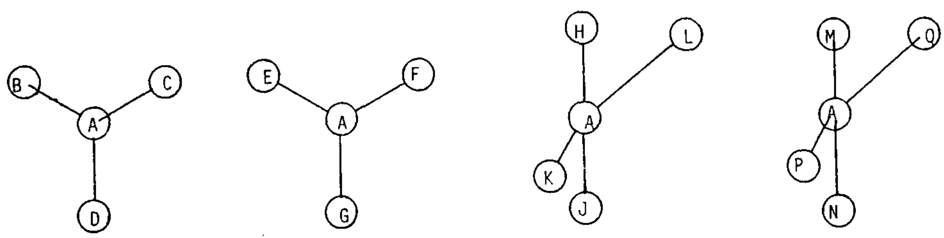
1. Consider the hypothetical molecules (1, 2, 3 and 4) represented below: (The bond lengths may not be equal.)



1 2 3 4

i) In which of the molecules are all the atoms in the plane of the paper?

ii) Which of the atoms are closer to you than the plane of the paper?

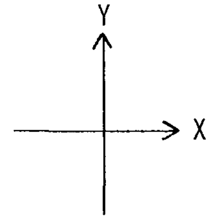
iii) Which of the atoms are further away from you than the plane of the paper?

State, in each case, which clue(s) in the diagrams helped you to come to your conclusion.

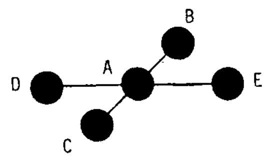
Remember:a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.

b) Atom A is in the plane of the paper.

c) All the bond lengths are equal.



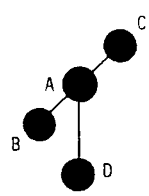
2. Consider the symmetrical square planar molecule represented below:



i) Which (if any) of the atoms B, C, D and E are not in the plane of the paper?

ii) Draw a diagram to show what this molecule would look like if all the atoms were in the plane of the paper.

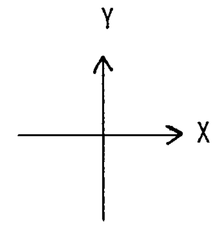
3. Consider the symmetrical T-shaped molecule represented below:



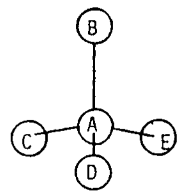
i) Which (if any) of the atoms B, C and D are not in the plane of the paper?
State which clue(s) in the diagram helped you to come to your conclusion.

ii) Draw a diagram to show what this molecule would look like if all the atoms were in the plane of the paper.

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

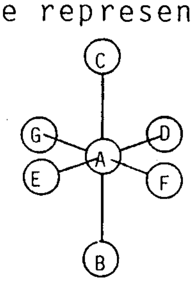


4. Consider the molecule represented below:



i) Which (if any) of the atoms B, C, D and E are not in the plane of the paper?
ii) Which (if any) of the atoms are closer to you than the plane of the paper?
iii) Which (if any) of the atoms are further away from you than the plane of the paper?

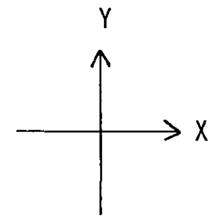
5. Consider the molecule represented below:



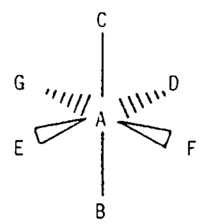
i) Which (if any) of the atoms B, C, D, E, F and G are not in the plane of the paper?
ii) Which (if any) of the atoms are closer to you than the plane of the paper?
iii) Which (if any) of the atoms are further away from you than the plane of the paper?

State which clue(s) in the diagram helped you to come to your conclusion.

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

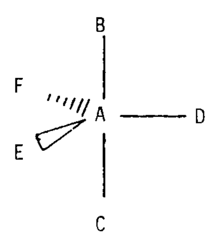


6. Consider the molecule represented below:



i) Which (if any) of the atoms B, C, D, E, F and G are not in the plane of the paper?
ii) Which (if any) of the atoms are closer to you than the plane of the paper?
iii) Which (if any) of the atoms are further away from you than the plane of the paper?

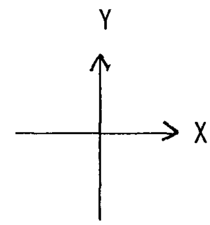
7. Consider the molecule represented below:



i) Which (if any) of the atoms B, C, D, E and F are not in the plane of the paper?
ii) Which (if any) of the atoms are closer to you than the plane of the paper?
iii) Which (if any) of the atoms are further away from you than the plane of the paper?

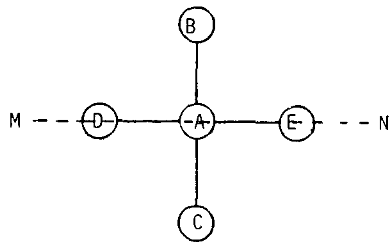
State which clue(s) in the diagram helped you to come to your conclusion, in each case.

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

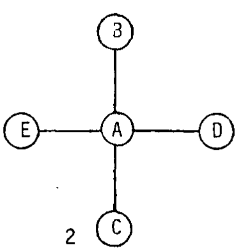


8. Consider the square planar molecule represented in diagram 1 below:

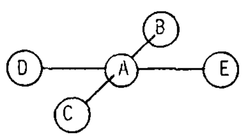
1



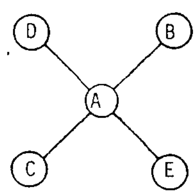
Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if you turned it around the axis corresponding to the dashed line MN?



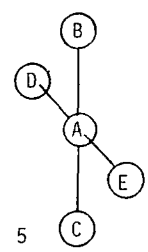
2



3



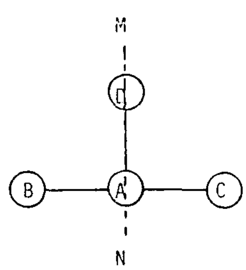
4



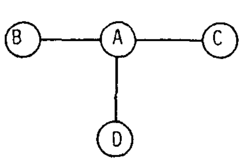
5

9. Consider the T-shaped molecule represented in diagram 1 below:

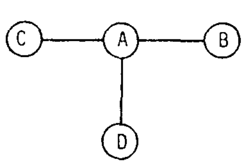
1



Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if you turned it around the axis corresponding to the dashed line MN?



2



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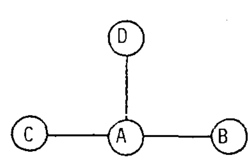
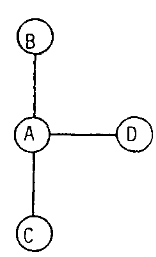
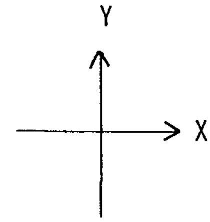


4



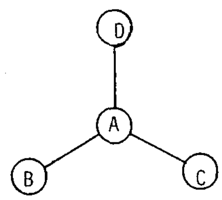
5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

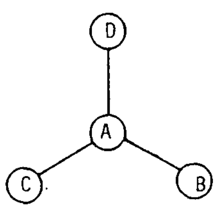


10. Consider the trigonal planar molecule represented in diagram 1 below:

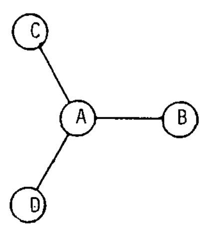
1



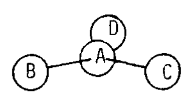
Imagine a line through Atom A coming straight out of the plane of the paper. Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if you turned it around the line?



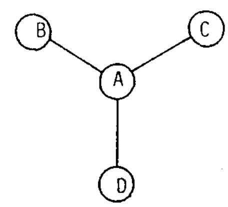
2



3



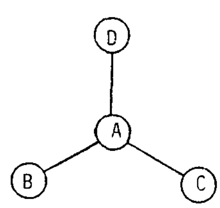
4



5

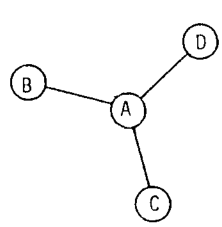
11. Consider the trigonal planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1

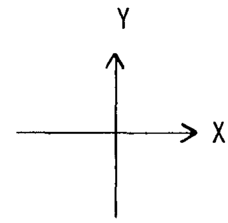


About which axis (X, Y or Z) must the molecule be rotated if it is to look like diagram 2?

2

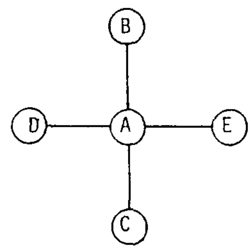


Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



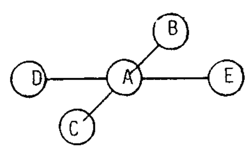
12. Consider the square planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1



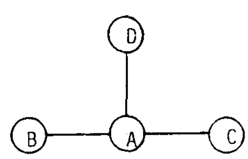
About which axis (X, Y or Z) must the molecule be rotated if it is to look like diagram 2?

2



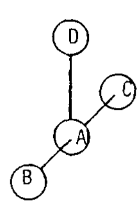
13. Consider the T-shaped molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1

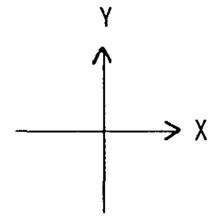


About which axis (X, Y or Z) must the molecule be rotated if it is to look like diagram 2?

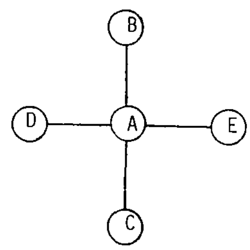
2



Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

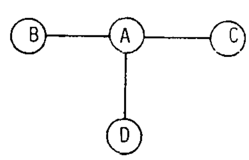


14. Consider the square planar molecule represented below, in which all the atoms are in the plane of the paper:



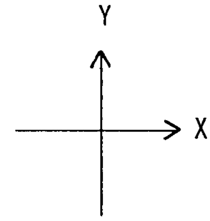
Which (if any) of the atoms A, B, C, D and E might not be in the plane of the paper if the molecule were rotated about the X-axis?

15. Consider the T-shaped molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

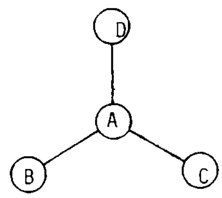


Which (if any) of the atoms A, B, C and D might not be in the plane of the paper if the molecule were rotated about the Y-axis?

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



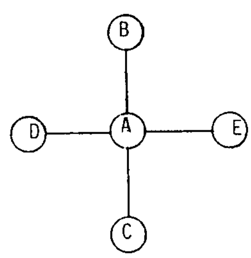
16. Consider the trigonal planar molecule represented below, in which all the atoms are in the plane of the paper:



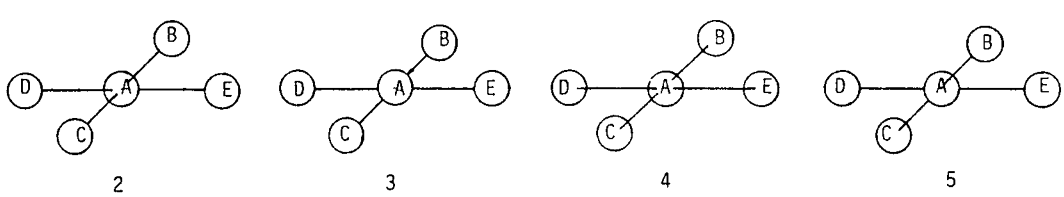
Which (if any) of the atoms A, B, C and D might not be in the plane of the paper if the molecule were rotated about the Z-axis?

17. Consider the square planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

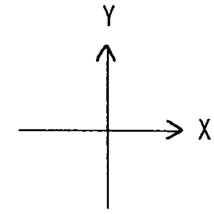
1



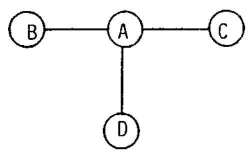
Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the X-axis?



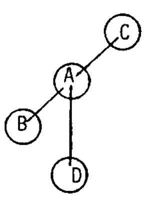
Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



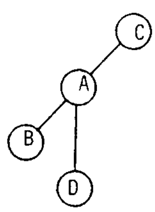
18. Consider the T-shaped molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1 

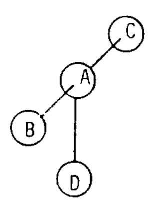
Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the Y-axis? State briefly how you came to your conclusion.



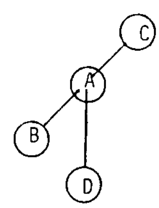
2



3

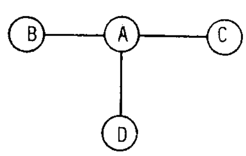


4

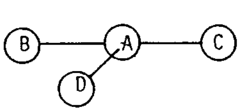


5

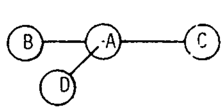
19. Consider the T-shaped molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1 

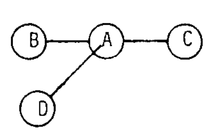
Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the X-axis?



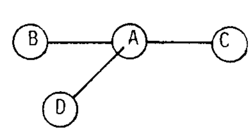
2



3

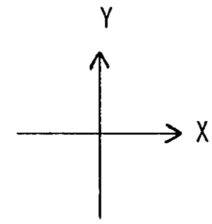


4

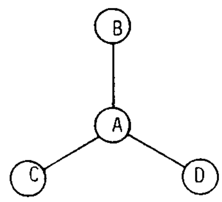


5

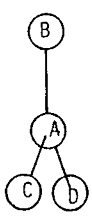
Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

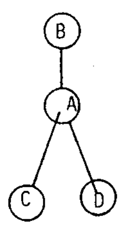


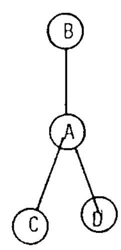
20. Consider the trigonal planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

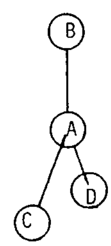
1


Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the Y-axis? State briefly how you came to your conclusion.

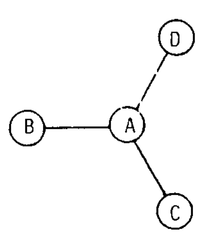

2


3

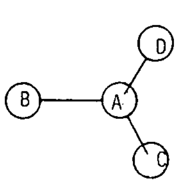

4

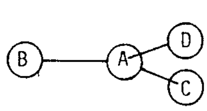

5

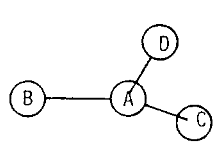
21. Consider the trigonal planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

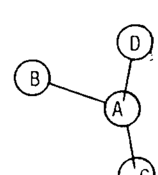
1


Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the X-axis?

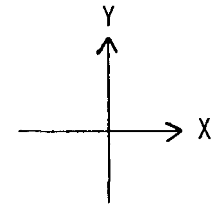

2


3


4

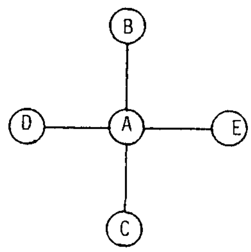

5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

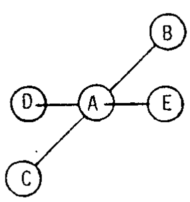


22. Consider the square-planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

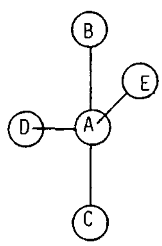
1



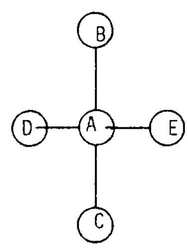
Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the Y-axis? State briefly how you came to your conclusion.



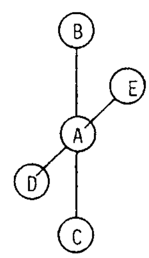
2



3



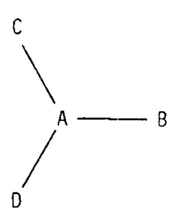
4



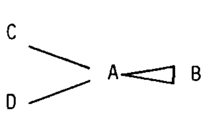
5

23. Consider the trigonal planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper

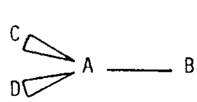
1



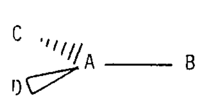
Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the X-axis?



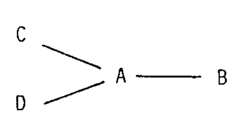
2



3

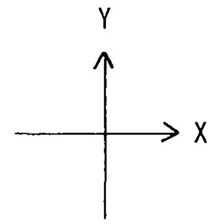


4



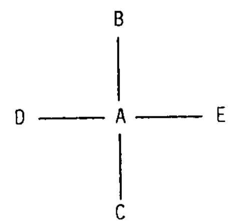
5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

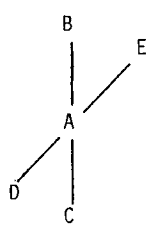


24. Consider the square planar molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

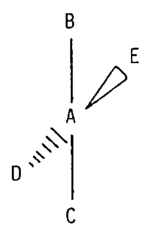
1



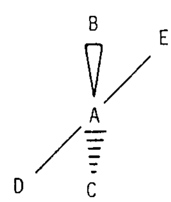
Which one of the diagrams (2, 3, 4 or 5) is the best representation of what the molecule could look like if it were rotated about the Y-axis? State briefly how you came to your conclusion.



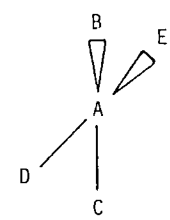
2



3



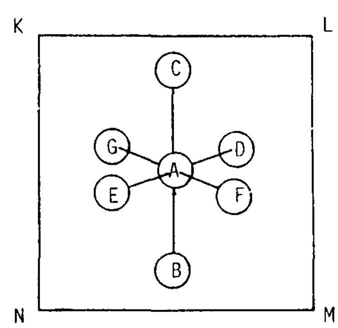
4



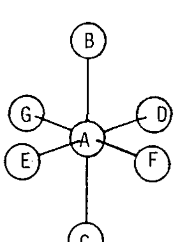
5

25. A square shaped mirror (KLMN) is placed behind an octahedral molecule as shown in diagram 1 below:

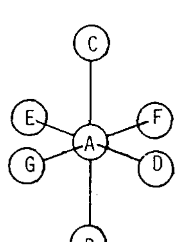
1



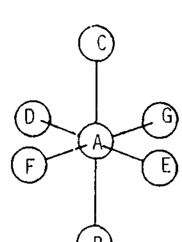
Which one of the diagrams (2, 3, 4 or 5) shows what the mirror image of the molecule would look like?



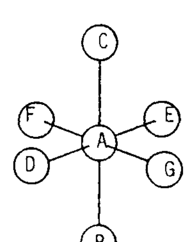
2



3

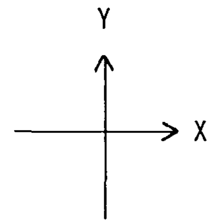


4



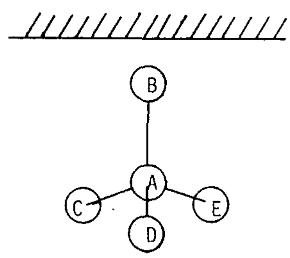
5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

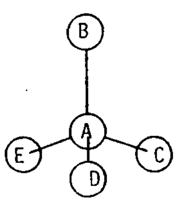


26. A mirror is in a plane perpendicular to the plane of the paper and a tetrahedral molecule is placed below the mirror as shown in diagram 1 below:

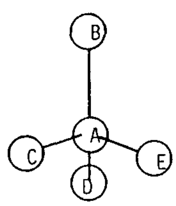
1



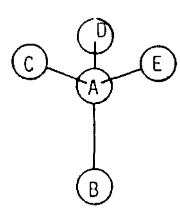
Which one of the diagrams (2, 3, 4 or 5) shows what the mirror image of the molecule would look like?



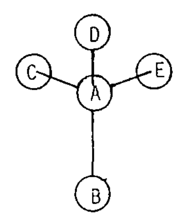
2



3



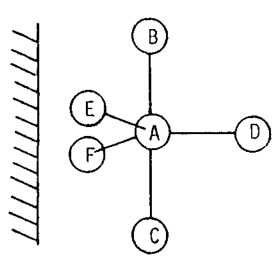
4



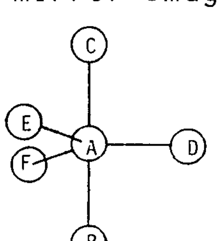
5

27. A mirror perpendicular to the plane of the paper is placed to the left of a trigonal bipyramidal molecule as shown in diagram 1 below:

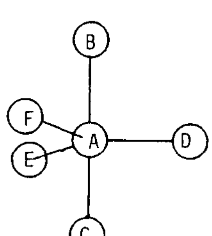
1



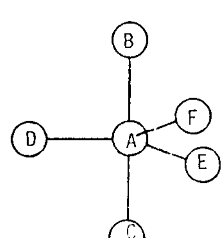
Which one of the diagrams (2, 3, 4 or 5) shows what the mirror image of the molecule would look like?



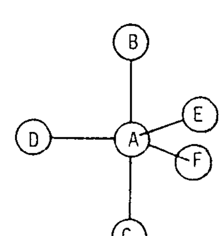
2



3

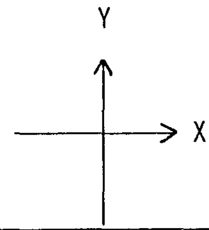


4



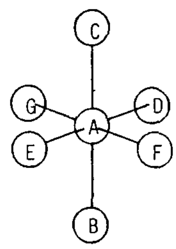
5

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



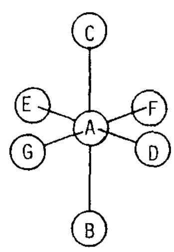
28. Consider the octahedral molecule represented in diagram 1 below. Atoms A, B and C are in the plane of the paper, atoms E and F are closer to you than the plane of the paper and atoms D and G are further away from you than the plane of the paper.

1



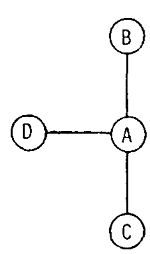
In which plane (XY, XZ or YZ) must the molecule be reflected if it is to look like diagram 2?

2



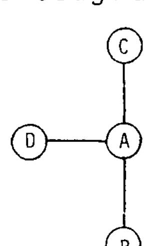
29. Consider the T-shaped molecule represented in diagram 1 below, in which all the atoms are in the plane of the paper:

1

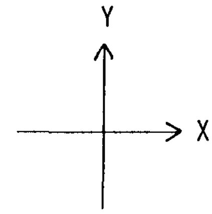


In which plane (XY, XZ or YZ) must the molecule be reflected if it is to look like diagram 2?

2

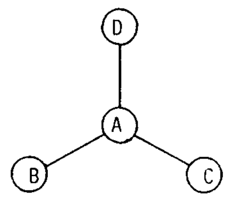


Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.



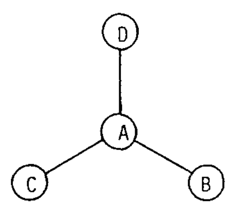
30. Consider the trigonal planar molecule represented below, in which all the atoms are in the plane of the paper:

1

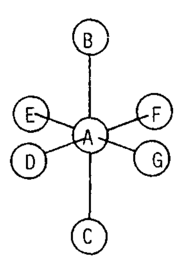


In which plane (XY, XZ or YZ) must the molecule be reflected if it is to look like diagram 2?

2

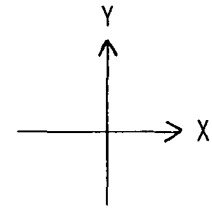


31. Consider the molecule represented below. Atoms A, B and C are in the plane of the paper, atoms D and G are closer to you than the plane of the paper, and atoms E and F are further away from you than the plane of the paper.

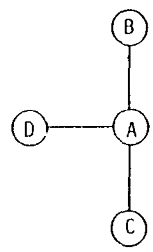


Which (if any) of the atoms would be closer to you than the plane of the paper if the molecule were reflected in the XY plane?

Remember: a) The X- and Y-axes are in the plane of the paper and the Z-axis is perpendicular to them and comes out of the plane of the paper.
b) Atom A is in the plane of the paper.
c) All the bond lengths are equal.

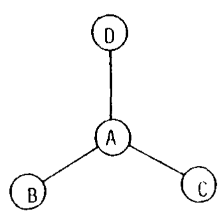


32. Consider the molecule represented below, in which all the atoms are in the plane of the paper:



Which atom would be closest to the top of the page if the molecule were reflected in the XZ plane?

33. Consider the molecule represented below, in which all the atoms are in the plane of the paper:



Which atom would be closest to the left hand side of the page if the molecule were reflected in the YZ plane?

APPENDIX 2

THE REMEDIAL INSTRUCTION PROGRAMME

1. Molecules are three-dimensional. The three dimensions are length, breadth and height; these are conventionally represented by three lines called axes, known as the X-, Y- and Z-axes.

2. The axes (see Figure 1)

The X-axis is the horizontal axis.
The Y-axis is the vertical axis.
The Z-axis is perpendicular to both the X- and Y-axes.

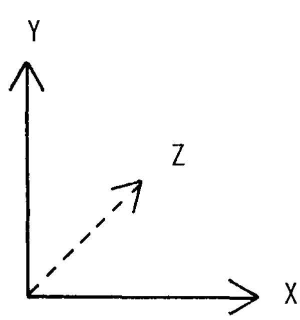


Figure 1. The axes

3. The planes

Space can be described by three flat surfaces called planes.

The plane involving the X- and Y-axes is the XY plane.
The plane involving the X- and Z-axes is the XZ plane.
The plane involving the Y- and Z-axes is the YZ plane.

4. Depth cues

Molecules and crystals have three-dimensional structures. When they have to be drawn on paper, we have to represent these three-dimensional structures in two dimensions. Conversely, we must also be able to visualise a molecule in three dimensions, the diagram of which is drawn on paper (in two-dimensions). To be able to look at a diagram of a molecule and visualise it three dimensionally, it is first necessary to decide

(a) which of the atoms in the molecule are in the plane of the paper,
(b) which of the atoms are closer to you than the plane of the paper,
(c) which of the atoms are further away from you than the plane of the paper.

To help answer these questions, clues (generally known as depth cues) must be provided in the diagrams.

When the molecule is represented by "ball and stick" structures three cues are commonly used in books to show depth. These are:

(a) overlap
(b) foreshortening of lines
(c) distortion of angles.

When dimensional formulae are used to represent structures of molecules, wedges and dashes are made use of to reveal bonds which are not in the plane of the paper.

We will now consider each of the above cues in turn.

4.1. The Overlap cue

The overlap cue is used to show which of two atoms is further away. Overlap is represented by drawing a line that goes into an atom. To illustrate this, consider diagrams (a), (b), (c) and (d) in Figure 2 below. In diagrams (a), (b) and (c) the line from atom B is seen to overlap atom A. This means that atom A is further away from you than atom B. Atoms in the plane of the paper are represented by drawing a line between them, without overlap. This is illustrated in diagram (d) where there is no overlap; this means that atoms A and B are in the plane of the paper.

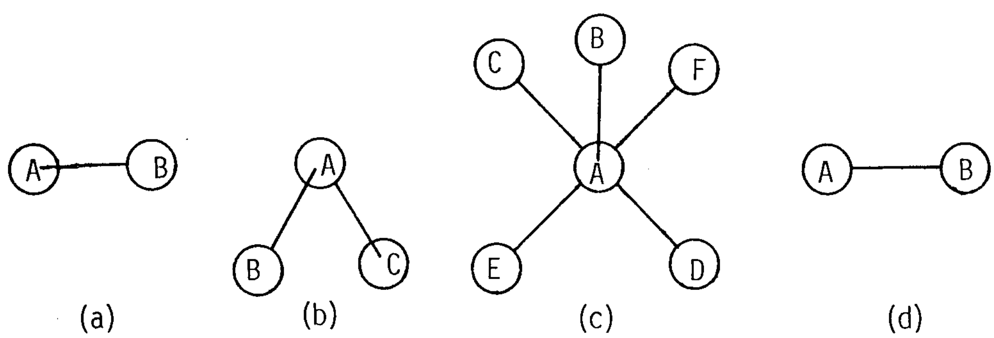


Figure 2. The overlap cue

Consider now a structure in which an atom A is bonded to a number of other atoms. To visualise the structure three-dimensionally the simplest method would be to assume that atom A is in the plane of the paper. You can then tell which atoms are further away from you, and which atoms are closer to you than the plane of the paper. Thus in Figure 3 below, C is further away from you than A, and A is further away from you than B. If A is considered to be in the plane of the paper, then C would be further away from you, and B closer to you, than the plane of the paper.

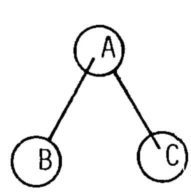
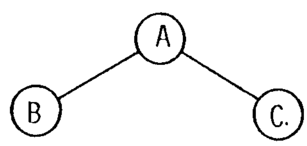
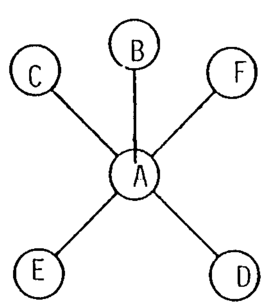


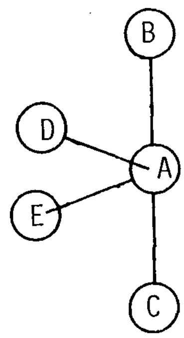
Figure 3. Use of the overlap cue

Exercise 1

Cover the right hand column which gives the correct answer with a piece of paper. Answer each question and then check the correctness of your answer.

		Answer
(a)	Consider the molecule represented below: 	
(i)	Is there any overlap in the above diagram?	No
(ii)	Are all the atoms in the plane of the paper?	Yes
(b)	Consider the molecule represented below. 	
(i)	Is there any overlap? If so, which atom overlaps which atom?	Yes. Atom B overlaps A
(ii)	Are all the atoms in the plane of the paper?	No
(iii)	Which atom/atoms are not in the plane of the paper? (Remember that the central atom A is assumed to be in the plane of the paper.)	B
(iv)	Which atom is further away from you, A or B?	A

Exercise 1 (continued)

		Answer
(c)	Consider the molecule represented below, in which atom A is in the plane of the paper: 	
(i)	Is there any overlap in the diagram above? If so, which atoms overlap which atoms?	Yes. Atom D overlaps A. Atom A overlaps E.
(ii)	Are all the atoms in the plane of the paper	No
(iii)	Which atoms are not in the plane of the paper?	D and E
(iv)	Which atom is further away from you, A or D?	A
(v)	Which atom is further away from you, A or E?	E
(vi)	Which atom is further away from you than the plane of the paper?	E
(vii)	Which atom is closer to you than the plane of the paper?	D

4.2. Foreshortening of lines.

Foreshortening of lines is used as a cue to indicate in a diagram those atoms that are not in the plane of the paper.

For simplicity we shall restrict ourselves to molecules in which all the bond lengths are equal. If all the atoms are in the plane of the paper, then all the bonds would be drawn the same length, as indicated in Figure 4 (a) below. If an atom (say D - see Figure 4 (b)) is not in the plane of the paper, then the line joining D to another atom (say A) would be drawn shorter than the other bond lengths. We say that the line AD is foreshortened.

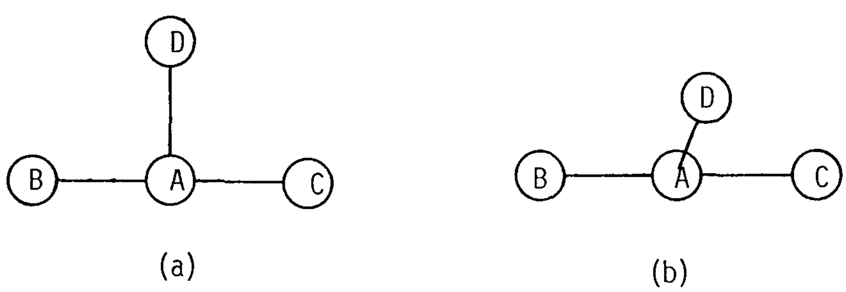


Figure 4. Foreshortening of lines

The line is drawn shorter whether the atom is closer to you, or further away from you, than the plane of the paper. This is illustrated in diagrams (a) and (b) in Figure 5 below. Line AD is foreshortened in both diagrams. However, from the overlap cue it can be seen that atom D is closer to you than the plane of the paper in diagram (a), and that atom D is further away from you than the plane of the paper in diagram (b).

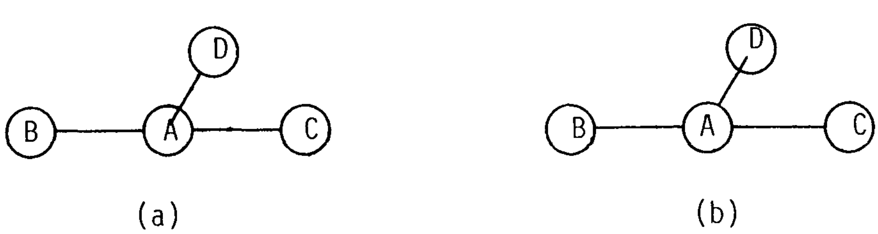
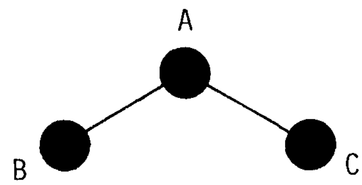
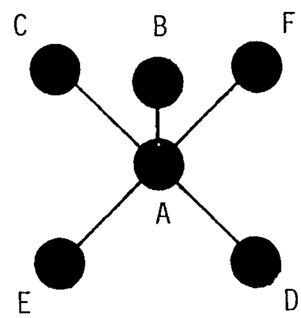
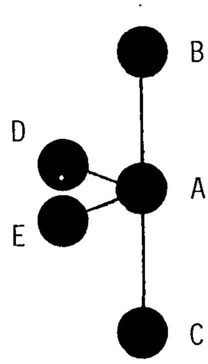


Figure 5
Limitations of the foreshortening of lines cue

Exercise 2

		Answer
(a)	Consider the molecule represented below, in which all the bonds have the same length: 	
(i)	Are all the atoms in the plane of the paper?	Yes
(b)	Consider the molecule represented below, in which all the bonds have the same length: 	
(i)	Are all the atoms in the plane of the paper?	No
(ii)	Which atom/atoms are not in the plane of the paper?	B
(c)	Consider the molecule represented below, in which all the bonds have the same length: 	
(i)	Are all the atoms in the plane of the paper?	No
(ii)	Which of the atoms are not in the plane of the paper?	D and E
(iii)	Can you say which of the atoms is closer to you than the plane of the paper?	No, can't answer.

4.3. Distortion of angles

Distortion of angles is another cue used to denote depth in diagrams; here an angle is drawn a different size from the size it is in the molecule. As an example, consider a T-shaped molecule; the bond angles in this molecule are 90°. If all the atoms are in the plane of the paper then the molecule can be represented as shown in Figure 6 below: note that the bond angles (90°) in the Figure are the correct angles.

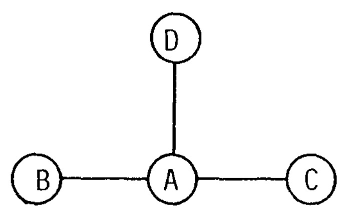


Figure 6. T-shaped molecule

If an atom (say D) in this T-shaped molecule were not in the plane of the paper, then the angles between D and the other atoms would be distorted. This can be seen in Figure 7 below; angles DAB and DAC are distorted.

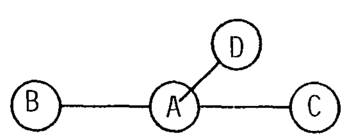


Figure 7. Distortion of angles

Relative usefulness of the three cues

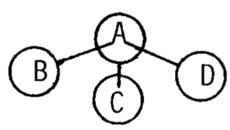
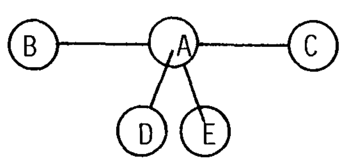
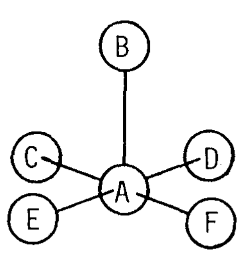
Of the three cues, the overlap cue is the most important. Remember that this cue alone is sufficient for deducing unambiguously the three-dimensional structure of a molecule.

Exercise 3

For each of the molecules represented below, state:

(i) which of the atoms are closer to you than the plane of the paper;

(ii) which of the atoms are further away from you than the plane of the paper.

	Answer
(a) 	i) B and D ii) C
(b) 	i) D ii) E
(c) 	i) E and F ii) C and D

4.4. Wedge and dash notation

Another way of representing the three-dimensional structure of a molecule is by using wedges, dashes and lines. As examples consider diagrams (a), (b) (c) and (d) in Figure 8 below. You can see that bonds have been represented in three ways: , and . A bond coming out of the plane of the paper towards you is represented by a wedge, , a bond going into the plane of the paper away from you is represented by dashes, , and a bond in the plane of the paper is represented by a line, .

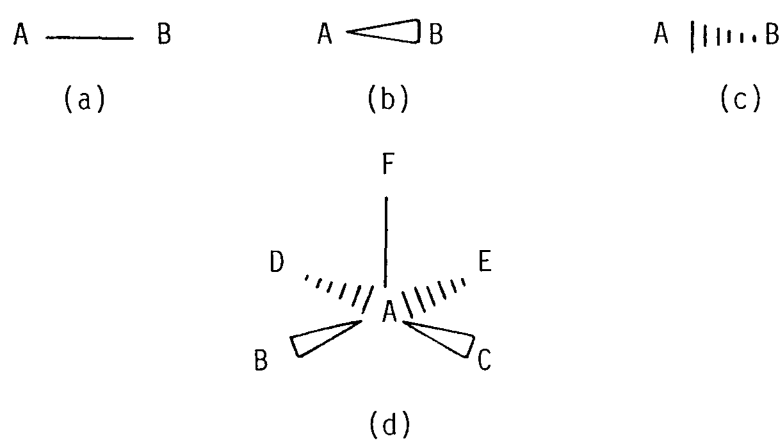


Figure 8. Wedge and dash notation

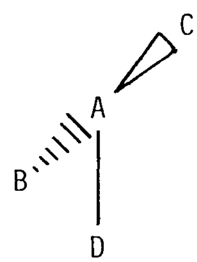
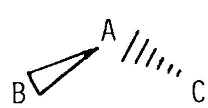
A line represents a bond in the plane of the paper; in diagram (a), A and B are, therefore, both in the plane of the paper; the same is true for A and F in diagram (d). A wedge represents a bond coming out of the plane of the paper. In diagram (b), B is therefore closer to you than A; similarly, B and C are closer to you than A in diagram (d). Dashes represent a bond going into the plane of the paper, this means that B is further away from you than A in diagram (c); similarly D and E are further away from you than A in diagram (d).

Exercise 4

For each of the molecules represented below, state

(i) which of the atoms are closer to you than the plane of the paper;

(ii) which of the atoms are further away from you than the plane of the paper.

		Answer
(a)		(i) C (ii) B
(b)		(i) B (ii) C
(c)		(i) D (ii) E

5. Rotation and Reflection

In chemistry, you are sometimes required to visualise the effects of an operation on a diagram of a molecule. We will restrict ourselves to the operations of rotation and reflection. In order to visualise the effects of these operations you must be able to:

(a) visualise the three-dimensional structure of the molecule (with the help of the depth cues)
(b) visualise the operations (rotation, reflection)
(c) visualise the molecule after rotation or reflection.

5.1. Rotation

Rotation is the operation in which a molecule is turned around one of the three axes, X, Y and Z.

Figures 9, 10 and 11 below illustrate rotation around the X-, Y- and Z-axes respectively. Compare the diagrams with a model of the axes.

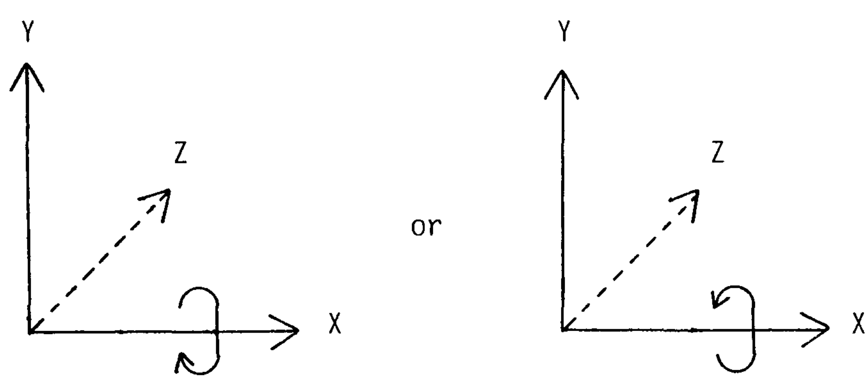


Figure 9. Rotation (turning) around the X-axis

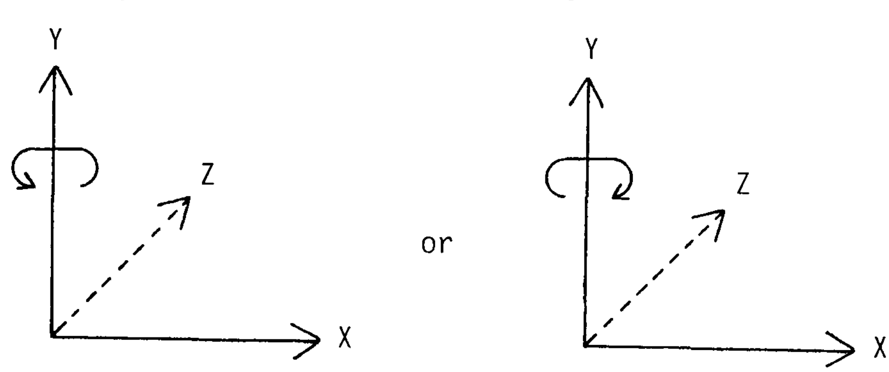


Figure 10. Rotation (turning) around the Y-axis

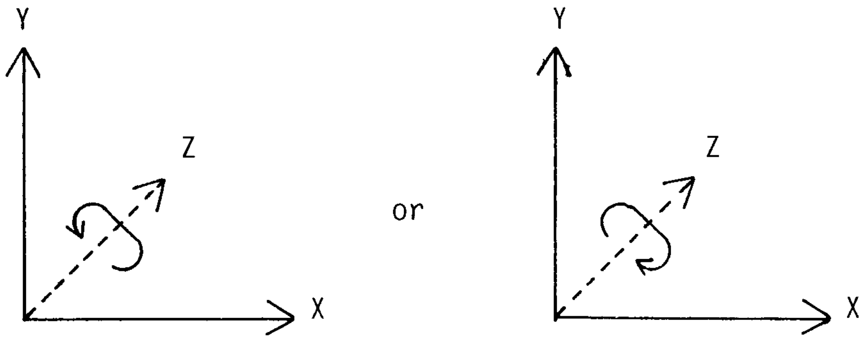


Figure 11. Rotation (turning) around the Z-axis

When a molecule is rotated, some of the atoms may change position. Atoms lying along the axis about which rotation takes place would not change position during rotation, but all other atoms would. Let us consider rotation about each axis in turn. In the following diagrams (Figures 12, 13 and 14), assume that atom A lies at the origin of the axes; this means that all the axes pass through atom A.

5.1.1. Rotation about the X-axis

When a molecule is rotated about the X-axis, atoms which lie along the X-axis would not change position, but the other atoms may change position. As an example, consider diagram (a) in Figure 12. Atoms A, B and C will remain in the plane of the paper, and will not change position when the molecule is rotated about the X-axis. Atom D may not be in the plane of the paper after rotation. This is illustrated in diagram (b).

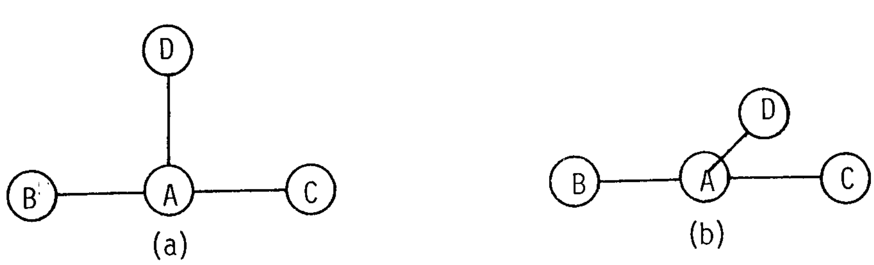


Figure 12. Rotation about the X-axis

5.1.2. Rotation about the Y-axis

When a molecule is rotated about the Y-axis, atoms which lie along the Y-axis would not change position. As an example, consider diagram (a) in Figure 13 below. Atoms A and D will remain in the plane of the paper when the molecule is rotated about the Y-axis. Atoms B and C may not be in the plane of the paper after rotation. This is illustrated in diagram (b).

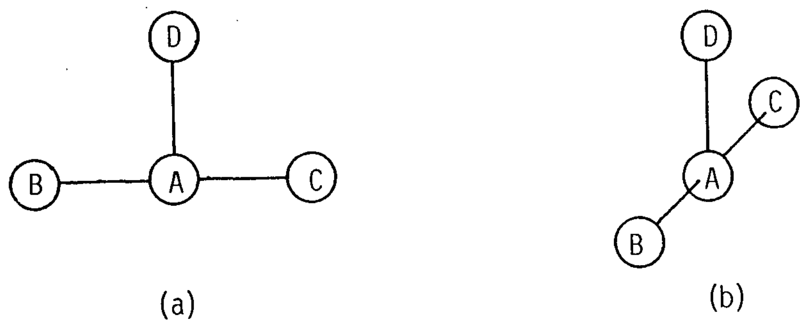


Figure 13. Rotation about the Y-axis

5.1.3. Rotation about the Z-axis

When a molecule is rotated about the Z-axis the atoms which do not lie along the Z-axis may change position. For example, when the molecule represented in diagram (a) in Figure 14 below is rotated about the Z-axis, atoms A, B and C change position, but they would remain in the plane of the paper. Since Atom D lies along the Z-axis, it would not change position. This is illustrated in diagram (b).

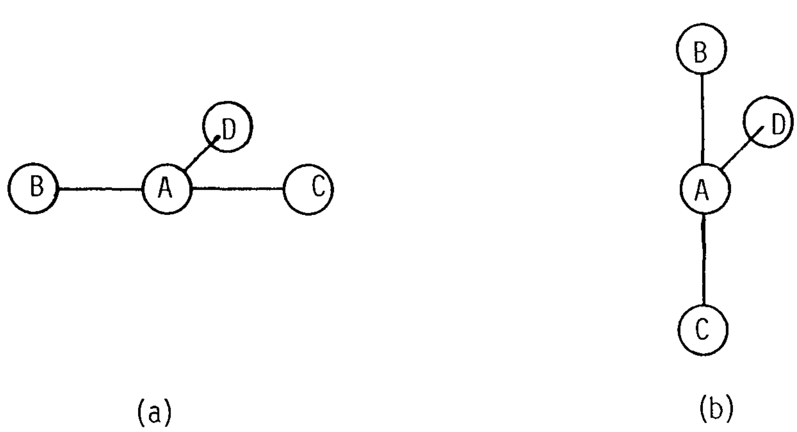
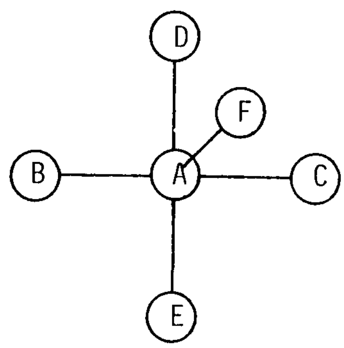


Figure 14. Rotation about the Z-axis

Exercise 5

		Answer
	Consider the molecule represented below: 	
(i)	Which (if any) of the atoms B, C, D, E and F might not be in the plane of the paper if the molecule were rotated about the X-axis?	D, E and F
(ii)	Which (if any) of the atoms B, C, D, E and F might not be in the plane of the paper if the molecule were rotated about the Y-axis?	B, C and F
(iii)	Which (if any) of the atoms B, C, D, E and F might not be in the plane of the paper if the molecule were rotated about the Z-axis?	F

5.2. Reflection

Reflection is the operation which would lead to the "mirror image" of the molecule. An image in a plane mirror would be at the same distance behind the mirror as the object is in front of it. Therefore, if an atom is close to the mirror, the reflection of that atom will also be close to the mirror. We will now consider, in turn, reflection in the XY, XZ and YZ planes.

5.2.1. Reflection in the XY plane

The atoms in a molecule which are closest to you will be furthest away from you after reflection, and vice versa. This is illustrated in Figure 15 below. Atom B in the molecule is further away from you than atom A; in the reflection it would hence be closer.

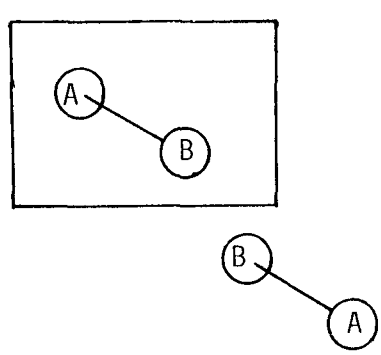


Figure 15. Reflection in the XY plane

5.2.2. Reflection in the XZ plane

Atoms at the top in the molecule will be at the bottom after reflection. This is illustrated in Figure 16 below. Atom B is higher up than atom A in the molecule; in the reflection it will hence be lower down.

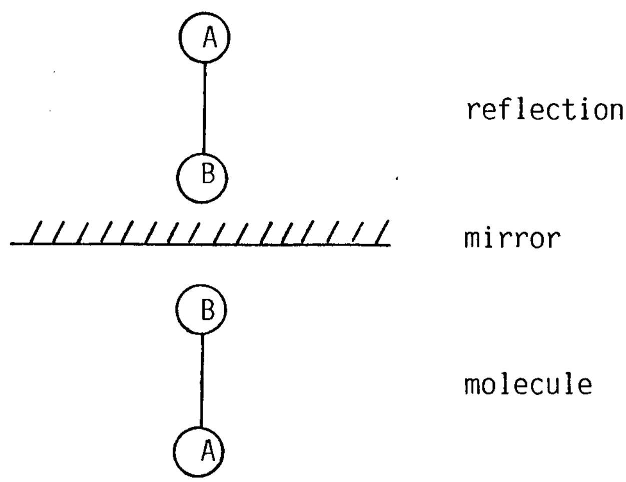


Figure 16. Reflection in the XZ plane

5.2.3. Reflection in the YZ plane

Atoms at the right hand side of the molecule will be at the left hand side after reflection. This is illustrated in Figure 17 below. Atom B is to the right of atom A in the molecule, but to the left of atom A in the reflection.

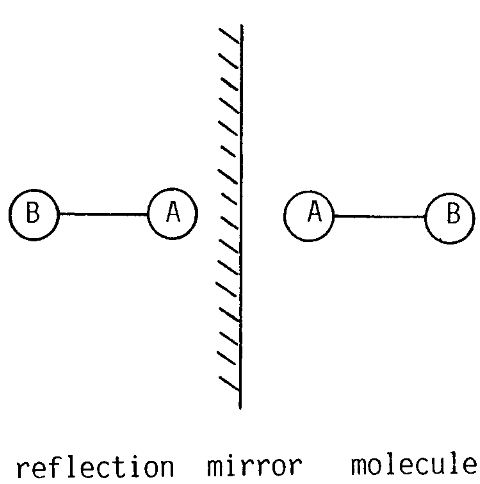
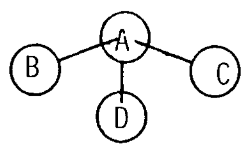
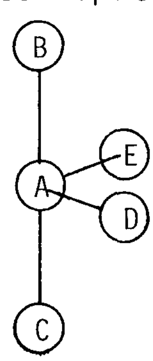
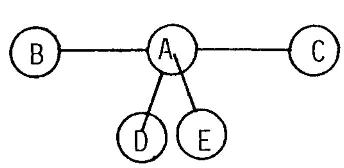


Figure 17. Reflection in the YZ plane

Exercise 6

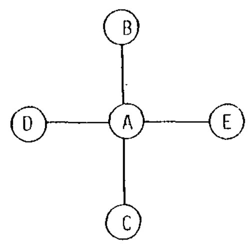
	Answer
(a) Consider the molecule represented below:  Which (if any) of the atoms would be closer to you than the plane of the paper if the molecule were reflected in the XY plane?	D
(b) Consider the molecule represented below:  Which atom would be closest to the top of the page if the molecule were reflected in the XZ plane?	C
(c) Consider the molecule represented below:  Which atom would be closest to the left hand side of the page if the molecule were reflected in the YZ plane?	C

Exercise 7

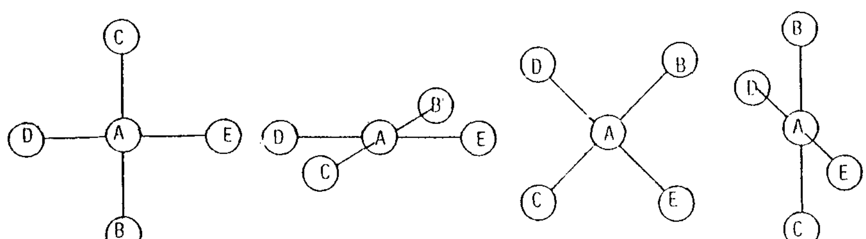
Answer

(a) Consider the square planar molecule represented in diagram 1 below:

1



Which one of the diagrams (2, 3, 4 or 5) shows what the molecule could look like if it were rotated about the Y-axis?

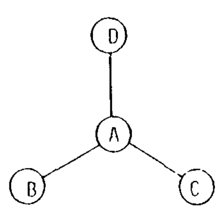


2 3 4 5

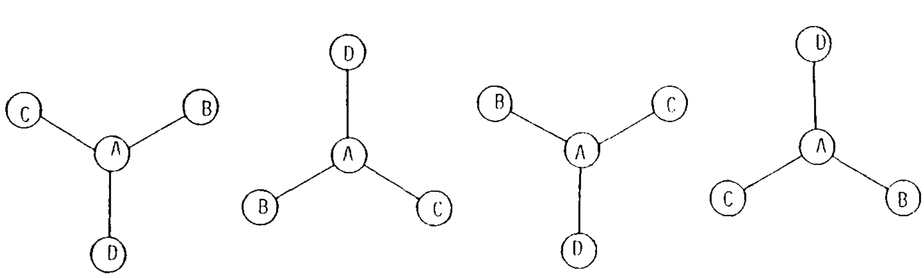
Answer: 5

(b) Consider the trigonal planar molecule represented in diagram 1 below:

1



Which one of the diagrams (2, 3, 4 or 5) shows what the molecule would look like if it were reflected in the XZ plane?



2 3 4 5

Answer: 4

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