# CHAPTER 4

# METHODOLOGY

## Introduction

Research on students' mechanistic reasoning is not easy to conduct because the cognitive processes occurring in the minds of the students cannot be observed directly. The overall aim of the research is to explore students' mechanistic reasoning for several biological processes related to the Theory of Cell. This chapter describes the methods and procedures of the present study and how the research questions were investigated. A detailed account of the methods for each stage is discussed. The methodology of this study will be presented and discussed in the following sections:

a. Preparation of instruments
b. Pilot study
c. Planning of the Living Cell Tool
d. Actual study

## Preparation of Instruments

In order to check the feasibility of the study, the researcher constructed the first draft of the instruments deemed important in this study. These three instruments are the Science Test, four Incoherency Tests and the Living Cell Tool. This was done to investigate the feasibility of the proposed study. How the researcher constructed the Science Test and the Incoherency Tests will now be discussed. Due to the complexity in preparing the Living Cell Tool, this section will only discuss the preparation of the Science Test and the Incoherency Tests. The preparation of the Living Cell Tool will be discussed in a different section entitled "Planning of the Living Cell Tool".

There are several different expert panels involved in validating the different instruments. The 3 expert panels who were involved in the preparation of these instruments are outlined in Table 1.

Table 4.1

*Expert Panels who were Involved in the Preparation of the Three Instruments*

| Instrument | Expert Panel | Label |
|---|---|---|
| **Science Test** | A group of experienced teachers who have taught Science for more than 8 years | Expert Panel A |
| **Incoherency Tests** | i. Three secondary school teachers with at least 8 years of experience in teaching Biology<br>ii. A lecturer who has been involved in Biology Education for more than 20 years from one of the local universities | Expert Panel B |
| **Living Cell Tool** | i. Two secondary school teachers with at least 8 years of experience in teaching Biology<br>ii. A lecturer who has been involved in Biology Education for more than 20 years from one of the local universities | Expert Panel C |

**The Science Test**

The aim of having a Science Test was to categorise the two different achievement levels of the participants, specifically high and low achieving students, in their knowledge of science. The researcher would emphasise that the categorisation of high and low achieving students were based on their overall Science knowledge that they had learnt in Forms One, Two and Three. Thus, the Science Test encompasses various topics and does not solely concentrate on topics which are related to Biology.

The first step in building the test was identifying the content boundaries of the science test as in the curriculum specification for Science in Forms One, Two and Three. The Science topics that were being accessed are shown in Table 4.2.

Table 4.2

*Science Topics in the Science Test*

| **Form** | **Science Topic** |
|---|---|
| **One** | • Cell<br>• Matter<br>• The variety of resources on the Earth<br>• The air around us<br>• Sources of energy<br>• Heat |
| **Two** | • The world through our senses<br>• Nutrition<br>• Biodiversity<br>• Water<br>• Pressure |
| **Three** | • Respiration<br>• Blood circulation and transport<br>• Reproduction<br>• Growth<br>• Electricity |

The Science content for Forms One, Two and Three were selected because the Form Four students who are the actual study sample should have already acquired this knowledge as they entered Form Four. Initially, discussions of the items in the Science Test were carried out with expert panel A (refer to Table 4.1) as well as by referring to the existing literature review. An example of an item that was adopted from the literature review and discussed with the expert panel A is shown in Table 4.3.

Table 4.3

*Example of an Item Adopted from the Literature Review and Discussed with Expert Panel A*

| **Item adopted from literature review** | **Item developed after discussion among the teachers** |
|---|---|
| 12. Respiration is a process of ________________.<br>*Respirasi adalah satu proses ________________.*<br>A converting glucose to oxygen.<br>*menukar glukosa kepada oksigen.*<br>B converting oxygen to glucose.<br>*menukar oksigen kepada glukosa.*<br>C taking in air into our bodies and giving out oxygen.<br>*mengambil masuk udara ke dalam badan dan menghembus keluar oksigen.*<br>D taking in air into our bodies and giving out carbon dioxide.<br>*mengambil masuk udara ke dalam badan dan menghembus keluar karbon dioksida.*<br>Answer: ( )<br>Sources: Boo (2005) | 6. Siti consumed fish during her lunch. Which of the following sequences of digestion is correct?<br>*Siti mengambil ikan semasa makan tengahari. Antara berikut yang manakah menunjukkan susunan proses penghadaman yang tepat?*<br>A mouth → stomach → duodenum → small intestine<br>B stomach → duodenum → liver → small intestine→ large intestine<br>C stomach → duodenum → small intestine<br>D mouth → stomach → liver → small intestine<br>Answer: ( ) |

Then, the construction of the multiple-choice test began and changes required were made after all the items were reviewed by the expert panel A again. A preliminary test with 40 students in a secondary school was carried out. Several alterations were made to the original test questions after carrying out the preliminary test among 40 students. An example of a correction made is shown in Table 4.4.

Table 4.4

*Example of Correction Made for an item of the Science Test*

| **Original Question** | **Corrected Question** |
|---|---|
| Question No. 18<br>In which organelle is photosynthesis carried out?<br>a. mitochondrion b. chloroplast<br>c. amyloplast d. vacuole | In which cellular component is photosynthesis carried out?<br>a. chlorophyll b. chloroplast<br>c. nucleus d. vacuole |

The final test which consists of 35 questions is shown in Appendix A.

**Incoherency tests**

The incoherency tests were constructed to uncover the problems most students face while learning biology processes especially related to the Theory of Cell (Cohen & Yarden, 2009; Flores, 2003; Kiboss, Ndirangu, & Wekesa, 2004; Riemeier & Gropengieβεr, 2008). Unable to apply underlying mechanistic reasoning, these students fail to link biological processes which are important to the understanding of the Theory of Cell. A total of 4 incoherency tests were developed for four sub-concepts of the Theory of Cell. The results from these tests helped in the construction of the third instrument of the study (The Living Cell Tool). The tests are known as the incoherency tests as the tests not only identify students' understanding of a certain concept but also their underlying reason for the understanding indicated. Students might be able to choose the correct answer; yet, the underlying reasoning might reveal the incoherency in their understanding of the concepts. Therefore, these tests are known as the Incoherency Tests throughout the study. The incoherency tests first draft was prepared for the 4 sub-concepts. The 4 sub-concept incoherency tests include:

i. Sub-concept 1 – Cell and its structure (First Test)

ii. Sub-concept 2 - Movement of substances across the plasma membrane (Second Test)

iii. Sub-concept 3 – Chemical composition of living cell (Third Test)

iv. Sub-concept 4 – Cell division (Fourth Test)

The researcher constructed the four tests with reference to the instruments constructed by previous researchers. For example, the second test for the sub-concept of movement of substances across the plasma membrane borrowed some ideas from Odom and Barrow (1995). Similarly, the forth test for cell division was based upon Lewis, Leach, and Wood-Robinson (2000a, 2000b) as well as Lewis and Wood-Robinson (2000c). The incoherency tests were constructed using similar procedures that have been employed in previous research (Jing-Ru, 2004; Odom & Barrow, 1995; Treagust, 1988; Wang, 2004) as the incoherency tests were two-tier tests. The construction of the first draft of tests took into consideration three phases which were: (a) define the content domain based on the Malaysian Form Four Biology curriculum specification, (b) Identify students' incoherent concepts from literature; and (c) development of the tests. The steps and procedures followed in the current study are presented in Table 4.5.

Table 4.5

*Steps and Procedures in the Construction of the Four Incoherency Tests' Instruments*

| Step | Tasks | Sequence of Procedures |
|---|---|---|
| **1** | Review Form Four biology curriculum specification | 1 |
| | Identify propositional knowledge statements | 2 |
| | Content validation | 3 |
| **2** | Review literature related | 4 |
| | Develop multiple choice questions with free response based on propositional knowledge statements and literature review | 5 |
| | Conduct multiple choice questions with free response test | 6 |
| | Conduct interview | 7 |
| | Refine test | 8 |
| **3** | Develop two-tier items | 9 |
| | Design a specific grid | 10 |

Table 4.5 (Continued)

| | |
|---|---|
| Items validation by expert panel | 11 |
| Conduct pilot test | 12 |
| Refine test | 13 |
| Conduct administration and statistical analysis | 14 |

The flowchart of instrument construction is shown in Figure 4.1.

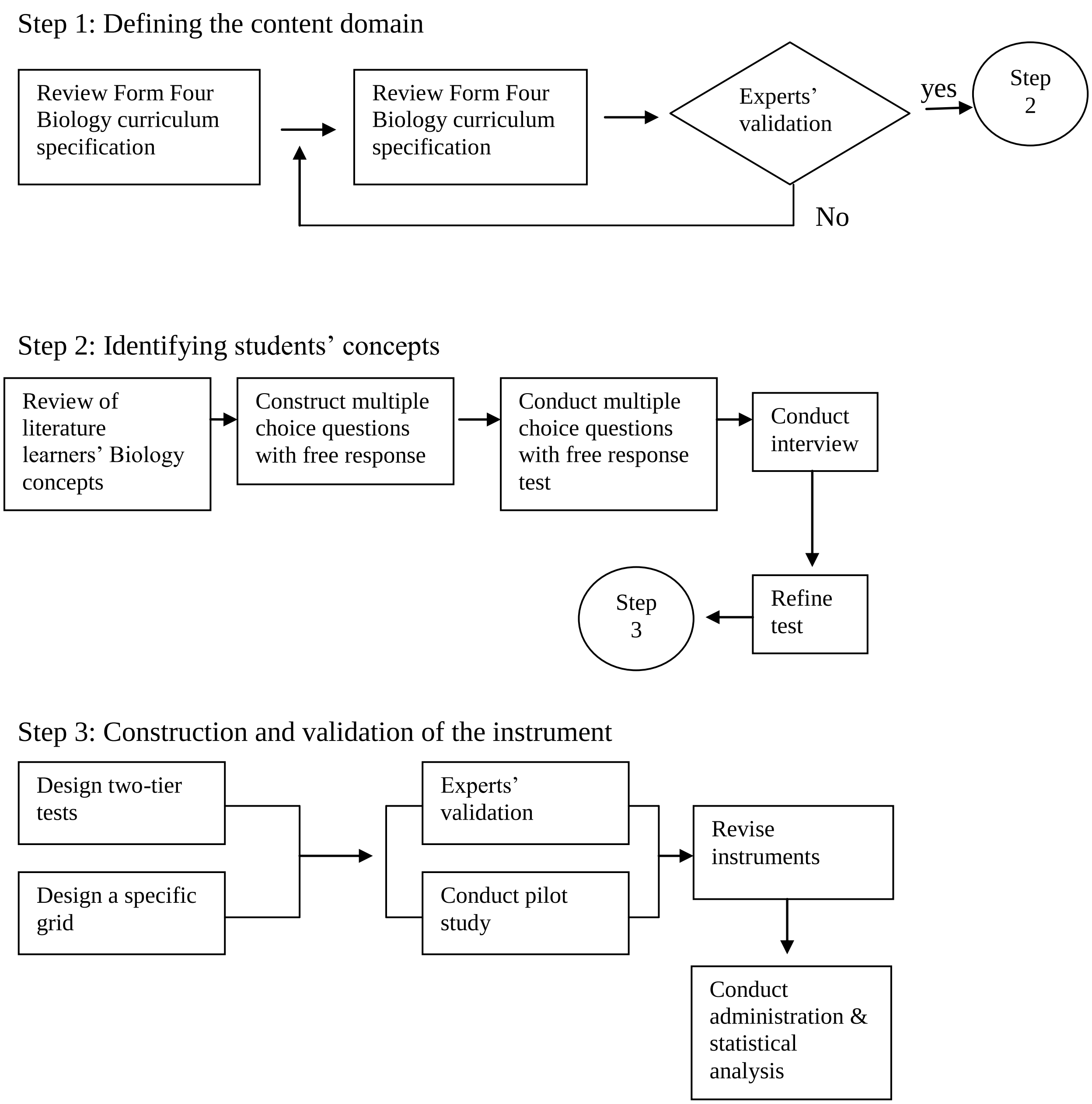



*Figure 4.1*. Instrument construction flowchart

**Step 1: Defining the content domain**

Step 1 of the incoherency tests construction process consisted of 3 procedures intended to define the boundaries for the students' understanding of the four concepts. Procedure 1 examined the current Form Four biology curriculum specifications (appendix B). This procedure provided direct propositional knowledge statements (step 2) across four sub-concepts. An example of propositional knowledge statements for sub-concept 1 cell structure and organisation based on the Biology curriculum specification involved were:

1. Cellular components of a cell which includes the plasma membrane, cell wall, cytoplasm and organelles.
2. Organelles in a cell consist of the nucleus, rough and smooth endoplasmic reticulum, mitochondria, golgi apparatus, lysosomes, ribosomes, chloroplast, centrioles and vacuoles.

The final version of propositional knowledge statements were validated by expert panel B (refer to Table 4.1) (procedure 3).

**Step 2: Identifying students' concepts**

Prior to the construction of the tests, students' concepts about the defined content were collected through related literature (procedure 4). Based on the literature and propositional knowledge identified in Step 1, a multiple choice with free response answers incoherency test for each sub-concept was constructed (procedure 5). The first tier in the incoherency tests were in multiple choice formats with two, three or four choices. The second tier had the statement "The reason for my answer is because," with a blank space provided. Students were required to explain the reason for their multiple-choice answer selection. All four incoherency tests were administered to 60 Form Four students after the students had studied the concepts (procedure 6). The free response data provided further evidence of students' incoherent concepts. An example of the item is shown in Figure 4.2.

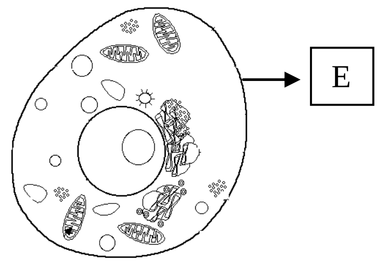
| Curriculum Specification | Question |
|---|---|
| **Structure of plasma membrane** |  1. What is the major component for E?<br>A Glycolipids<br>B Phospholipids<br>C Head and tail<br><br>The reason for my answer:<br>________________________________________<br>________________________________________ |

*Figure 4.2.* Development of a multiple choice with free response item

A follow up interview was conducted to assess students' pre-existing concepts more deeply (procedure 7). All the interviewees were students who had completed the lessons for these sub-concepts and had sat for the multiple choice test with free response answer tests. After the tests, students with no written reasons in the tests, or the reasons given in the test were vague and needed further clarifications were interviewed. An example of a part of an interview is shown in Table 4.6, related to the question shown in Figure 4.2.

Table 4.6

*A Student's Interview for Question 1*

| Students' answer | Reason | Interview |
|---|---|---|
| **B. Phospholipids** | Because it is made up of phospholipids | R : Why do you think it is made up of phospholipids?<br>S : Hm…because it is phospholipids<br>R : Can you explain as to what you understand about phospholipids?<br>S : (Silent). I think it has head and tail. This head and tail structure is phospholipids |

After the students' interviews, the tests were refined as some weaknesses were found in the tests. For example, some questions were confusing to the students and had to be corrected. In addition, certain terminologies which were deemed to be misleading (procedure 8) were changed.

### Step 3: Construction and validation of the instrument

The content domain defined in step 1 and students' coherent understandings documented in step 2 were used to develop the first version of the two-tiered multiple choice tests (procedure 9). The first tier consisted of a content question. The second tier consisted of possible reasons for the first part. An example is shown in Figure 4.3 based on the student's interview shown in Table 4.6.

**Question 1**

1. What is the major component for E?

   A Glycolipids.
   B Phospholipids.
   C Head and tail.

   The reason for my answer:

   A E is mainly made up of hydrophilic heads and hydrophobic tails.
   B E consists of two layers of carbohydrates and lipids.
   C E consists of two layers of phosphates and lipids.

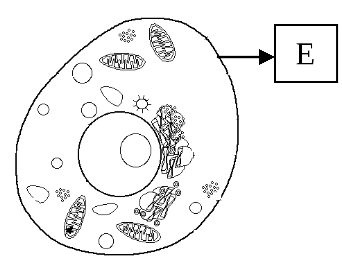



*Figure 4.3.* An example of a two-tier test for question 1

A table of specifications was constructed to ensure that the items covered all propositional knowledge statements (Appendix C) (procedure 10). All four incoherency tests were validated by the same panel of experts (procedure 11). All items were revised based on the experts' comments. A pilot test was conducted for all the four incoherency tests among Form Four students after they had learnt the concepts (procedure 12). Items in the incoherency tests were again revised, based on students' responses (procedure 13). The final version of the tests contained 16 items for cell structure and its function, 22 items for movement of substances across the plasma membrane, 23 items for chemical composition of cell and 24 items for cell division. The final versions of the tests were administered and analysed by using simple descriptive statistics. However, the data presented focused on students' incoherencies within a topic as well as across the topics instead of percentage.

The four sets of incoherency tests (after revision and correction) are attached in Appendix D.

## Pilot Study

Several aspects in conducting the pilot study will be discussed in this section. Overall, as a result of the pilot test, a reliability check for the incoherency tests and the science test was calculated by employing Spearman-Brown approaches. The incoherency tests and the science test were further modified and validated.

### Selection of Participants

The participants involved in the pilot study for the science test comprised 102 Form Three students, while 93 From Four science students from one government secondary school took part in the pilot study for the four incoherency tests.

In the actual study, the infusion was carried out from early January till May. The Form Four students of the actual sample had just completed their Form Three science curriculum the previous year and as yet have not been exposed to the Form Four curriculum. The Science test that was administered to the actual Form Four sample was based upon the Form Three curriculum , and thus was pilot tested among Form Three students because the actual Form Four student sample had only knowledge of the science they had studied till Form Three.  This Science test was used to categorise the Form Four students into high and low achieving levels for the infusion of mechanistic reasoning. The infusion was carried out starting in January whereby the sample was not exposed to any topic in Form Four Biology.

The incoherency tests in this study encompassed biological concepts which are taught only among the Form Four science students. Thus for this reason Form Four science students who have already studied the selected topics were selected to pilot test the incoherency tests.

**Pilot Study Procedures**

The pilot study of the Science test and Incoherency tests were carried out among Form Three and Form Four science students respectively. Both tests were administered in September 2010 after the students had studied these concepts.

As a result of the pilot study, a reliability check for the incoherency tests and the science test was calculated by employing Spearman-Brown approaches. Creswell (2008) stated that Spearman-Brown is suitable when the items on an instrument is scored right or wrong as categorical scores. In addition, the Spearman-Brown approach could estimate the full-length test reliability using all questions on an instrument; unlike the Kuder-Richardson split half test which relies on information from only half of the instrument. On the other hand, coefficient alpha is more suitable to examine consistency scores if the items are scored as continuous variables which are not utilised in the incoherency tests. Although there are no universal standards for reliability, split-half (error from items within the test) should normally exceed .80 for a good reliability while items above .70 are considered acceptable reliability (McKlevie, 2004).

The reliability test results for the science test and the four incoherency tests using the Spearman- Brown formula are reported in Table 4.7.

Table 4.7

*Reliability Using Spearmen-Brown for the Science Test and Incoherency Tests*

| **Test** | **Reliability** |
|---|---|
| Science test | 0.812 |
| **Incoherency Test** | **Reliability** |
| Cell structure and organization | 0.706 |
| Movement of substances across the plasma membrane | 0.808 |
| Chemical composition of the cell | 0.886 |
| Cell division | 0.875 |

## Analysis of the Incoherency Tests

This administration of the actual incoherency tests began in October 2010. The incoherency tests involved students from 3 government secondary schools in Selangor. Since the incoherency tests were conducted on different days for different set of tests, the numbers of students involved in the four tests were varied. Two hundred (200) students took the first incoherency test (cell structure and cell organization), 175 students were engaged in the second incoherency test (movement of substances across the plasma membrane), 206 students took the third test (chemical composition of cell) and 195 students were involved in the fourth test (cell division). Data obtained revealed students' incoherent understanding related to the Theory of Cell. The data obtained from the incoherency tests were analysed using a simple descriptive analysis.

An item was scored as correct in the incoherency test when both the desired content knowledge and reason answers were selected. The items were evaluated for both correct and incorrect response combinations selected using cross-tabulation in SPSS. For example, Table 4.8 shows response combinations selected for item 1 selected by students. It was found that 67.5% (n=135) correctly selected both the desired content knowledge and reason and only 1% (n=2) selected the desired content knowledge but an incoherent reason.

Table 4.8

*Percentage of Students' Selection of the Response Combination for Item 1 in the Incoherency Test*

| | | **Reason (%)** | | | **Total** |
|---|---|---|---|---|---|
| | | A | B | C | |
| **Choices** | A | 16 | 0 | 1 | 17 |
| | B | 0 | 0 | 2.5 | 2.5 |
| | C | 1 | 9 | 1.5 | 11.5 |
| | D | 0 | 1 | 67.5* | 68.5 |

n = 175
* Correct choice and reason

Based on descriptive data generated from SPSS, the researcher will only discuss the incoherencies that the majority of the students showed in the 'Planning of the Living Cell Tool' section. The analysis of the four incoherency tests was utilised for the preparation of the Living Cell Tool. The revised Living Cell Tool was further reviewed by expert panel C (refer to table 4.1). The finalized Living Cell Tool to explore students' mechanistic reasoning began in January 2011. This is elucidated in the following section.

**Planning of the Living Cell Tool Tasks**

In the beginning of the study, the researcher started with an idea of developing a tool to facilitate the infusion of mechanistic reasoning. Since students were not familiar with mechanistic reasoning, a tool was necessary to assist the infusion before they were able to do it on their own. Furthermore, a tool was required to collect the students' written responses to questions that reflected mechanistic reasoning and traced their reasoning over five months of infusion. Therefore, a tool was prepared, the Living Cell Tool. The Living Cell Tool was used to infuse students' mechanistic reasoning as well as a tool to collect students' mechanistic reasoning data. Students utilised this tool to write down their reasoning and the written mechanistic reasoning was analysed. The preparation of the tool will now be discussed.

The preparation of the first draft of the tool began with identifying the content boundaries as in the curriculum specification for biology Form Four (refer to appendix B) (Ministry of Education, 2005). Following this, the data obtained from the preliminary tests (multiple choices with free response answer) of the incoherency tests (refer to preparation of instruments section) given to the students was then referred. An example of an activity constructed based on the four incoherency tests is shown in Table 4.9.

Table 4.9

*An Example of Development of an Activity Based On One of the Four Incoherency Tests.*

| **Question 3** | **Students answer** | **Activity in the Living Cell Tool** |
|---|---|---|
| Why are the organelles in the cell membrane-bound?<br><br>A The membrane gives protection to the organelles.<br><br>B To avoid attachment of the organelles that might cause malfunction of the organelles.<br><br>C The organelles are highly specialised for specific function.*<br><br>* The correct answer | 75.6 % of the students chose A. | Refer Appendix E Cell structure and cell organization, page 10, Task 2 |

The content of the proposed tasks in the Living Cell Tool was then discussed with the expert panel C (refer to Table 4.1) and changes were made. Then, a preliminary test of the tool was conducted with 20 students in a secondary school. The test revealed that the present study was feasible.

In summary, students' incoherencies for the Theory of Cell were collected through four incoherency tests (each topic for one incoherency test) that were constructed by the researcher. The analysis of the incoherency tests were used to consolidate The Living Cell Tool by identifying students' incoherencies within a topic and across the topics. The details of how the Living Cell Tool was planned for the final utilisation based upon the incoherency tests in the present study will now be discussed for each of the four topics.

**Cell structure and organisation**

Students' incoherencies from the two-tier Incoherency tests were elicited. Few of the items, for example items 3, 7, 8, 12, 15, were found to be particularly difficult by the majority of students. Table 4.10 indicates students' incoherencies for the cell structure and organisation.

Table 4.10

*Incoherencies in Students' Understanding*

| Item | Content | The incoherencies |
|---|---|---|
| **1** | Organ and cell | Eyes, hairs and nails do not look like organs and will not develop into tissues |
| **2** | Definition of organelle | Chloroplast is not an organelle because it only exists in plant cells |
| | Types of organelle | |
| **3** | Nucleus | Only nucleus has DNA because it controls cell's activities |
| **5** | Nucleus | Is not involved in protein synthesis because ribosome synthesizes protein not the nucleus |

Table 4.10 (Continued)

| | | |
|---|---|---|
| **7** | Golgi apparatus, lysosomes and vesicles | Lysosomes exist naturally in cell. |
| **8** | Mitochondrion | Liver cells do not require high density of mitochondria because detoxification in liver does not require large amounts of energy |
| **12** | Mitochondrion | Only protein synthesis requires mitochondrion because the process involves more organelles. |
| | Cellular Process | |
| **10** | Protein synthesis | SER involves in protein synthesis because it helps to transport protein from RER to golgi body |
| **11** | Lipid synthesis | Ribosome involves in lipid synthesis |
| | Cell Organisation and specialisation | |
| **13** | Heart (animal) | Only made up of muscle tissues because it pumps blood |
| **14** | Stem (plant) | Only made up of xylem because xylem transports water and minerals |
| **15** | Genetic with cell specialisation | A basic cell will not form different cells because they have different characteristics. |

For item 1 (organ and cell), students did not perceive that hairs, nails and eyes are made up of different tissues such as epidermal tissues. In item 2, chloroplast is membrane-bounded and suspended in cytoplasm; thus, it is an organelle. However, the students were unable to comprehend the meaning of an organelle, and this led students to think that a chloroplast is not an organelle as it only exists in plant cells.

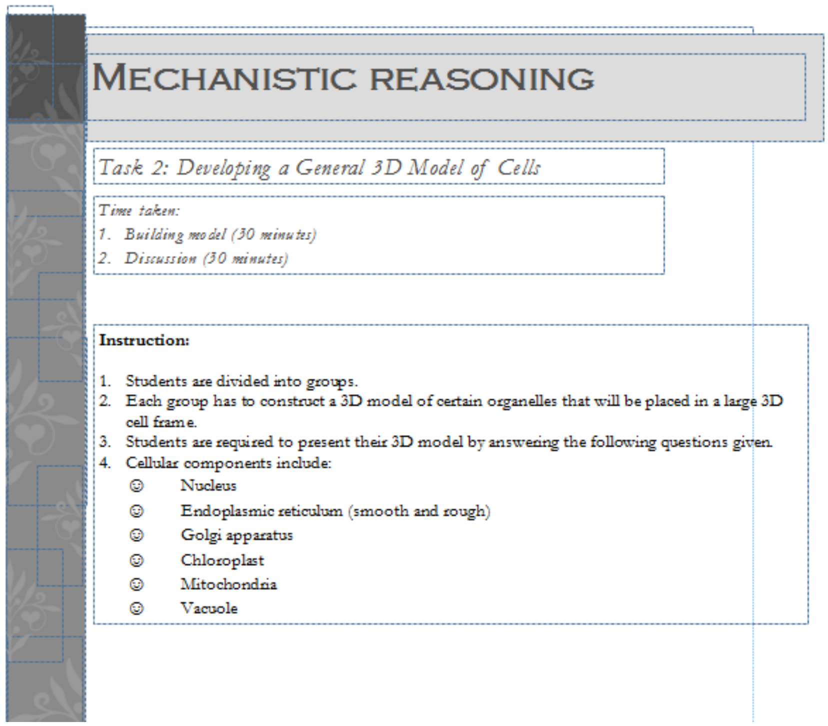
It appears that students' incoherencies mainly came from the incomplete understanding of the organelles. Among 5 items that were identified to be difficult by students (mentioned above), 4 of them were related to the function of the organelles. Students showed inconsistency in understanding the nucleus, mitochondria and lysosome. They presumed that the nucleus controlled all cellular activities but is not involved in protein synthesis (item 5). In addition, students thought that the nucleus controls the cell's activity because it has DNA (item 3). In fact, mitochondria and chloroplast also consist of

DNA even though they do not control the cell's activities. Protein synthesis requires DNA to initiate the process.

Secondly, the students seemed to believe that the mitochondrion generates energy for certain processes such as protein synthesis (item 12), and cellular processes such as detoxification. However, they also believed that the lipid synthesis process does not require energy because they do not involve many organelles (item 8). Energy generated by the mitochondrion does not depend on the number of organelles involved in a process. As for lysosomes (item 7), students thought that they exist naturally in cells. Although students had learned that lysosomes contain hydrolytic enzymes (a type of protein), they were unable to relate that the enzyme is synthesised in the ribosomes.

Without a clear understanding of the functions of the organelles, students encountered difficulties in relating the organelles in cellular processes for instance protein synthesis (item 10) and lipid synthesis (item 11). Smooth endoplasmic reticulum (SER) plays a part in lipid synthesis while rough endoplasmic reticulum (RER) does likewise in protein synthesis as it consists of ribosomes. Students were also unable to comprehend cell organisation and specialisation as they have had a weak understanding at the cellular level. For example from items 13 and 14, it can be seen that students believed that an organ is made up of one type of tissue. The fact is, an organ is made up of several types of tissues in order to carry out its function. For item 15, a basic cell will undergo cell specialisation to form different types of cells although the genetic constitution of all cells is similar. These incoherencies revealed students' surface understanding of cell organisation as well as cell specialisation. They might have known the definition for these concepts; yet, the underlying meaning of the functions and processes were not well-comprehended.

Based on the above incoherency test results, several activities such as Tasks 2, 3 and 5 were constructed for the first topic (Refer to Appendix E). An example of the task (task 2) is shown in Figure 4.4.



MECHANISTIC REASONING

*Task 2: Developing a General 3D Model of Cells*

*Time taken:*
*1. Building model (30 minutes)*
*2. Discussion (30 minutes)*

**Instruction:**

1. Students are divided into groups.
2. Each group has to construct a 3D model of certain organelles that will be placed in a large 3D cell frame.
3. Students are required to present their 3D model by answering the following questions given.
4. Cellular components include:
   - ☺ Nucleus
   - ☺ Endoplasmic reticulum (smooth and rough)
   - ☺ Golgi apparatus
   - ☺ Chloroplast
   - ☺ Mitochondria
   - ☺ Vacuole

*Figure 4.4.* An example of the task (task 2) which was prepared based on students' incoherencies

**Movement of substances across the plasma membrane**

Numerous incoherencies for this topic were found especially from items that involved multiple concepts. This indicated that the more connections students were required to make, the more difficulties the students encountered.

Table 4.8 showed students had more incoherencies for this topic. Students were able to choose the desired content knowledge for items 1, 3, 9, 10, 12, and 21, but the reasoning selected by the students indicated the incoherency of their understanding. On the other hand, items 2, 4, 5, 6, 7, 11, 13, 15, 18, 20 and 21 were largely answered inaccurately by students at the content knowledge level. Table 4.11 indicates the incoherencies that were found in students' understanding.

Table 4.11

*Incoherencies in Students' Understanding*

| Item | Content | The Incoherencies |
|---|---|---|
| | Plasma Membrane | |
| **1** | Structure of plasma membrane | The plasma membrane is made up of phospholipids bilayer because it consists of head and tail. |
| **2** | Structure of plasma membrane | Different organelles have different membrane structure because they function differently. |
| **3** | Structure of plasma membrane | The head is polar while the tail is non-polar because the head does not consist of charges while the tail has. |
| | Passive Transport | |
| **9** | Simple diffusion | Particles in simple diffusion will move from a region of high concentration to a low concentration because they tend to move to both regions until they are isotonic to each other and the particles will stop moving. |
| **10** | Simple diffusion | When two areas' concentration increases the rate of diffusion will increase because the molecules have less space to move.<br>When two areas of concentration increases, the rate of diffusion will decrease because the molecules spread less at higher concentration. |
| | Structure of the plasma membrane, properties of the substances and types of movement | |
| **4** | Structure of plasma membrane and types of movement. | Protein in required for osmosis because water is a large molecule. |
| **5** | Type of substances, properties of plasma membrane and types of movement | Ion $Na^+$ and $K^+$ can only move across the plasma membrane through active transport which depends on the concentration gradient.<br>Oxygen moves across the plasma membrane via simple diffusion or facilitated diffusion because it moves from high to low concentration. |
| **6** | Structure of plasma membrane and properties of plasma membrane | Only small and polar molecules can pass through the phospholipids because a polar molecule is readily dissolved in hydrophobic phase of lipids. |

Table 4.11 (Continued)

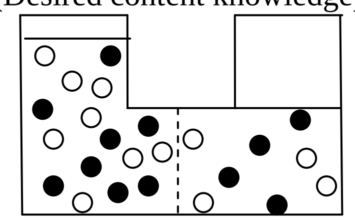
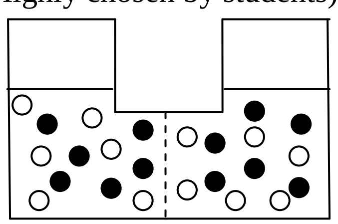
| | | |
|---|---|---|
| **20** | Structure of plasma membrane, type of substances, properties of plasma membrane and type of movement | Ionic molecules can pass through the phospholipids because phospholipid is highly permeable to ions.<br>Glucose is a small molecule because it is the simplest form of carbohydrate.<br>Glucose moves across the plasma membrane by simple diffusion because they are small molecules |
| **21** | Structure of plasma membrane, type of substances, properties of plasma membrane and type of movement | Glucose requires pore protein while ions $Na^+$ and $K^+$ require carrier protein because all ions move across the plasma membrane by active transport<br>Glucose (carrier protein), water (no protein required), $Na^+$ (pore protein), ions $Na^+$ and $K^+$ (carrier protein) (desired content knowledge) because all ions require carrier protein in active transport and facilitated diffusion. |
| | Application of passive transport in different substances | |
| **11** | Hypotonic, hypertonic and isotonic solutions | 10% of salt solution is hypotonic to 15% of salt solution (desired content knowledge) because a hypertonic solution signals more water molecules and less dissolved particles.<br>10% of salt solution is hypertonic to 15% of salt solution because a hypertonic solution signals more water molecules and less dissolved particles. |
| **13** | Hypotonic, hypertonic and isotonic solutions and passive transport | B. (Desired content knowledge)<br><br>C. (Highly chosen by students)<br><br>Water and sucrose will move from one side to another until equilibrium is reached |
| **15** | Effect of passive transport in living organisms | Osmosis and diffusion will stop when a cell dies because everything will stop functioning. |
| **18** | Passive transport in living organisms in animal cells | The preparation of salted fish involves simple diffusion because water diffuses out from the cell. |

Table 4.11 (Continued)

| | |
|---|---|
| | The preparation of salted fish involves simple diffusion because salt will diffuse into the cell and kill the bacteria. |
| | The preparation of salted fish involves osmosis because salt will diffuse into the cell and kill the bacteria. |

Students were able to explain that the plasma membrane is made up of phospholipids (item 1); however, they perceived the phospholipids bilayer as a head and tail structure rather than the chemical components which are phosphate groups and lipids that make up the structure. In addition, confusion occurred in differentiating the head and tail into polar and non-polar molecules. Most of the students reasoned that the head is polar because it does not consist of charges when it is supposed to be the other way around – the head is polar because it consists of electric charges (item 3). Since the organelles function differently, students believed that the structure of the plasma membrane must be different. However, the function of the membrane in every organelle is actually similar (item 2).

In accessing students' understanding of a single concept, for example, diffusion (items 8, 9 and 10), they were able to define diffusion. Nonetheless, the understanding underlying the concept indicated an incoherency among the students. For instance in item 9, the movement of particles in simple diffusion will reach an equilibration. However, students equated equilibration with an isotonic solution. Even in an isotonic solution, the molecules will not stop moving. They will still continue to move at an equal rate. Consequently, when two areas of concentration increase, the rate of diffusion will increase because the kinetic energy increases in the region of higher concentration.

Students' incoherency appeared to increase when they were required to relate the structure of plasma membrane and properties of the substance with types of movement (based on items 4, 5, 6, 7, 20 and 21). As a result, the students failed to integrate the concepts together and the concept remained fragmentary. The core of difficulty in answering these items appeared to be that students were unable to identify the properties of the substances that moved through the plasma membrane. For instance in item 7, students thought that glucose molecules were small and not polar as these molecules are the simplest form of carbohydrates. Even though glucose is the simplest form of carbohydrate, it is still a larger molecule as compared to the plasma membrane. As a result of the inability to identify the property of the substances, students encountered problems in matching the appropriate movement and the protein involved. For example in item 4, osmosis does not require a protein as water molecules are small enough to pass through the plasma membrane. Yet, students reasoned that osmosis required transport proteins as water molecules are large. Students also appeared to believe that the movement of oxygen molecules involved simple diffusion or facilitated diffusion to pass through because it moves from a region of high concentration to a lower concentration (item 5) while glucose involved simple diffusion as it is a small molecule (item 20). In reality, oxygen is small enough to pass through the plasma membrane. Therefore, the movement of oxygen only involves simple diffusion. As mentioned above, glucose is a large molecule as compared to the plasma membrane; thus, the movement of glucose involved facilitated diffusion which required a carrier protein and not a pore protein (item 21). Since non-polar molecules are more readily dissolved in the hydrophobic phase of lipids, ions and ionic molecules require a transport protein as they are not lipid-soluble (item 6). However, not all ions move across the plasma membrane via active transport. Some ions move across the plasma membrane by facilitated diffusion which requires pore protein.

Students had fewer obstacles with questions related to the application of passive transport (items 11, 13, 15 and 18) as well as the comparison between active transport and passive transport (items 19 and 22). Nonetheless, there were a few students were confused between hypotonic and hypertonic solution (item 11). A hypotonic solution has less dissolved particles while a hypertonic solution has more dissolved particles. In item 13, the majority of the students selected diagram C (refer Table 4.11) as they reasoned that sucrose and water molecules will move from one side to another until equilibrium is reached. However, the sucrose molecules are too large to pass through the semi-permeable membrane and only water molecules are allowed to move from one side to another as it is small enough. Therefore, the desired diagram should be B instead of C (refer Table 4.11). A similar incoherency was revealed in item 18 when students reasoned that during the preparation of salted fish, the salt will diffuse into the cell and kill bacteria. Salt is too large to pass through the membrane of the cell. Therefore, water will diffuse out of from the cell and bacteria, and will create an environment which is not conducive for the growth of microorganisms. Even though the cells had died, osmosis and simple diffusion will still occur as the cell does not have to be alive to carry out those processes (item 15). Nonetheless, the majority of students thought that once the cell had died, all the processes would stop functioning.

Based on the analysis of students' incoherencies, activities such as tasks 4, 6 and 8 in the second topic were planned in the Living Cell Tool *(*Refer Appendix E). An example of the task (task 4) is shown in Figure 4.5.

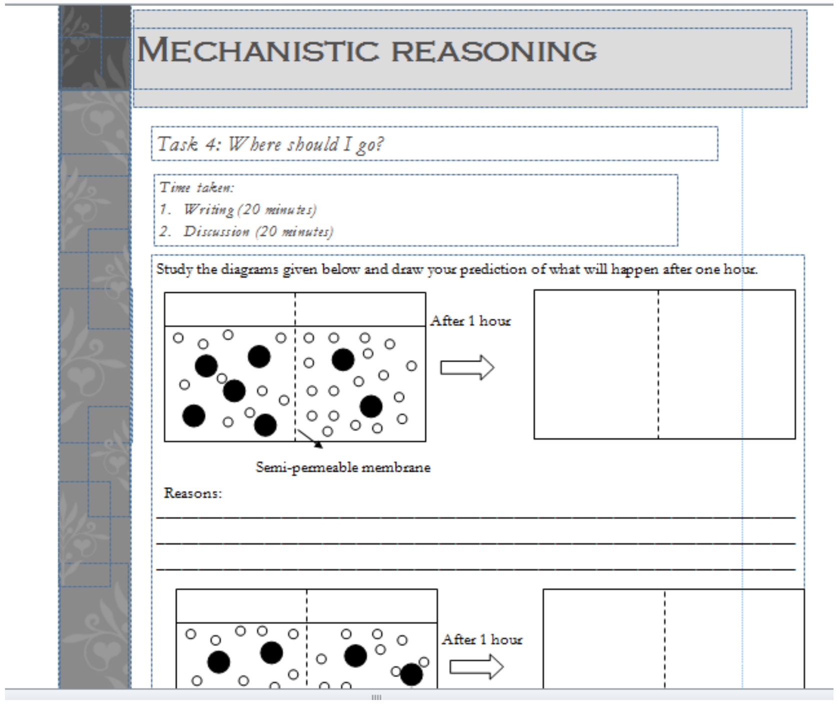



*Figure 4.5.* An example of the task (task 5) which was prepared based on students' incoherencies

**Chemical composition of the cell**

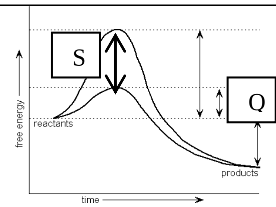
The researcher noticed that students had higher incoherencies as compared to the previous two concepts even though the questions were only at the comprehension and analysis levels based upon Bloom's taxonomy. This indicated that students had a very weak foundation for this topic. This might have been due to the fact that this topic required students to relate with their understanding in chemistry. Table 4.12 indicates the incoherencies that were found in students' understanding.

Table 4.12

*Incoherencies in Students' Understanding*

| Item | Content | The Incoherencies |
|---|---|---|
| **1** | Organic compound | Vitamins, lipids and nucleic acids are organic compounds (desired content knowledge) because they consist of chemical elements. |
| **4** | Monomer and polymer | The monomer for glycogen is glucose (desired content knowledge) because a polymer is named after its monomer.<br>The monomer for polypeptide is peptide because a polymer is named after its monomer |
| | Hydrolysis and condensation process | |
| **5** | Condensation process | A glucose which binds with a glucose is known as condensation process because it involves addition of water molecules. |
| **6** | Hydrolysis process | Only water is needed in the hydrolysis process because adding water can break the maltose structure. |
| | | Water and enzymes are needed in the hydrolysis process because adding water can break the maltose structure. |
| **7** | Hydrolysis process | Hydrolysis process only occurs in breaking down polysaccharides and disaccharides (inaccurate content knowledge) because all macromolecules must undergo hydrolysis to become simpler forms of molecules (desired reason) |
| | Organic Compounds | |
| **2** | Importance of water | "Water is a component in blood and fluid surrounded the cells" is a statement that does not indicate its importance |
| **3** | Classes of carbohydrate | Glucose - monosaccharide<br>Sucrose - disaccharide<br>Starch – polysaccharide<br>Are matched wrongly because glycogen is made up of 2 monomers which is a disaccharide. |
| **8** | Reducing sugar | Fructose and maltose are reducing sugars (desired content knowledge) because they can be broken down into simple form of sugars. |
| **9** | Protein structure | Structure Q (alpha-helix and beta-pleated sheet) is a primary structure because it is the simplest form of protein. |
| **10** | Protein structure with organ | The protein structure for hair (with diagram) is secondary level (desired content knowledge) because it is made up of $\alpha$-helix and $\beta$-sheet. |
| **11** | Saturated and unsaturated fatty acids | Saturated fatty acids increase LDL level because LDL is a good cholesterol. |
| **12** | Lipids | All unsaturated fatty acids are good lipids which will not cause health problems. |

Table 4.12 (Continued)

| | | |
|---|---|---|
| | Cell and chemical composition | |
| **13** | Cell wall | Cell wall is made up of lipids and carbohydrates so that the cell can expand and withstand pressure. |
| **14** | Plasma membrane | Plasma membrane is made up of lipids and protein because it has phospholipids bilayer and carrier protein. |
| **15** | Mitochondria | Mitochondria are made up of protein and lipids to generate energy in the form of ATP. |
| | Enzyme | |
| **16** | Activation energy in enzyme |  S is activation energy for an enzyme catalysed reaction while Q is activation energy for non-catalysed reaction because enzymes increase the energy for substrates to have more energy to bind with enzymes. |
| **17** | Enzyme characteristics | Digestive enzymes are intracellular and extracellular enzyme because amylase is secreted in the mouth while pepsin is secreted in the stomach. |
| **18** | Intracellular and extracellular enzyme | Both diagrams are intracellular enzyme because the process takes place in the cell. |
| **21** | Enzyme synthesis with organelle | Mitochondrion is not required in protein synthesis because the process does not require energy |
| | | Mitochondrion is not required in protein synthesis because mitochondrion provides energy for the body not protein synthesis |
| **22** | Factors affecting enzyme activity | The enzymatic reaction will decrease if more substrates are added because all enzymes are being occupied. |
| **23** | Factors affecting enzyme activity | The enzymatic reaction will increase if more enzyme is added (with the same amount of substrate) because increasing the enzyme will increase the rate of reaction |

Items 1 and 4 were related to the general use of terminology for the concept. Students were able to match the desired examples; yet, the reasoning revealed students' weak understanding. An organic compound, in students understanding, was a compound that consists of chemical elements instead of compounds that consist of carbon elements. Similar to item 4, students viewed polymer as named after monomer rather than monomer as the simplest form of molecules that bind together to form a polymer.

The item related to hydrolysis and condensation (item 5, 6 and 7) also suggested a lack of understanding of the underlying concept. The condensation process involves removal of water molecules while the hydrolysis process involves addition of water molecules. Confusion between both processes was obvious when students tried to answer item 5 (refer Table 4.12). Most students did not recognise the importance of enzymes in assisting these processes which might be due to learning these topics in isolation (item 6). An incoherency was found in item 7 between the reason and the desired content knowledge selected by students. Although students claimed that the condensation process only occurred in polysaccharides and disaccharides which is an incorrect answer for content knowledge; yet, they reasoned that all macromolecules will undergo the condensation process to become simpler forms of organic compounds (the desired reason). This might be due to the word ‘macromolecule’ which the students would not have understood.

For items related to organic compounds (2, 3, 8, 9, 10, 11 and 12), students possessed less incoherency in relation to lipids (items 11-12) than carbohydrates and proteins. Several incoherencies in understanding carbohydrates were revealed. Firstly, the reason chosen by the students was not consistent with the chosen content knowledge. For example for item 3, the majority of students selected that glucose belongs to the monosaccharide group, sucrose belongs to the disaccharides group and starch belongs to the polysaccharides group; however, the reason largely selected was ‘glycogen is made up of two sugar structures which is not a polysaccharide’ which is not consistent with the chosen answer. Secondly, in item 8 students had to choose which of the carbohydrates is a reducing sugar. Students might have been able to choose the types of carbohydrate which is known as reducing sugar; however, almost half of them who chose the desired content knowledge perceived reducing sugar as sugar that could be broken down into a simpler form. Reducing sugar actually refers to sugar that can reduce copper (II) to copper (I) in Benedict's solution.

The items related to protein indicated that students had incoherent understanding of the protein structure. For instance in item 9, the structure shown in the diagram was secondary structure because it has folded into alpha-helix and beta-pleated sheet; nonetheless, students perceived it as a primary structure as it is the simplest form of protein. The analysis for item 10 revealed that students were able to recognise the protein level by choosing the desired content knowledge. Nonetheless, students' reasoning showed that they were unable to distinguish between a α-helix and β-pleated sheet of the secondary protein structure in the diagram. This was because majority of them chose the hair structure as made up of α-helix and β-pleated sheet while the structure in the diagram only showed α-helix. As for lipids (items 11-12), students were unable to relate saturated and unsaturated fatty acids to low density lipoprotein (LDL) and high density lipoprotein (HDL). Saturated fatty acids will increase the LDL level as LDL will contribute to cholesterol deposition. Although unsaturated fatty acids are often known as 'good' lipids, not all unsaturated fatty acids are good and will not cause health problems (item 12).

Students were especially weak in items that investigated the chemical composition that made up the plasma membrane. Students did not perceive carbohydrates as a vital component in plasma membrane. They presumed that the membrane is only made up of lipids and protein as the membrane consists of phospholipids and carrier protein. Students often related the chemical composition of an organelle to its function. For example in items 13 and 14, students believed that a cell wall has lipids and carbohydrates so that the cell can expand and withstand pressure while mitochondria are made up of protein and lipid to generate energy. The cell wall is mainly made up of carbohydrates because the major components in the cell wall are cellulose. Mitochondria are made up of carbohydrates, lipids and proteins as it consists of a membrane (phospholipids bilayer, glycolipids) and matrix (enzyme which is a type of protein).

The students' understanding towards an enzyme was inadequate especially when differentiating extracellular and intracellular enzymes (item 18). The students associated the types of enzyme with the location of the organ. As a result, they had difficulties in answering the item related to the characteristics of enzymes (item 17). An intracellular enzyme is an enzyme that is synthesised and used within a cell while an extracellular enzyme is an enzyme that is synthesised in the cell but is secreted outside for use. Therefore, digestive enzymes are extracellular enzymes as they are secreted outside the cell to function.

Together with a weak understanding of extra- and intracellular enzymes, students also faced problems in comprehending activation energy of an enzyme (item 16). Not only were students unable to differentiate between activation energy catalysed by enzymes and which is not, they did not appear to have coherence understanding between activation energy and the characteristic of an enzyme. Very few students could understand that the reaction is sped up as the enzyme lowers the activation energy.

Items 19-21 assessed students' knowledge about the enzyme synthesising process which indicated less incoherency. Nonetheless, the result was consistent with the findings in cell structure and organisation. Firstly, students did not recognize the role of the nucleus in the enzyme synthesising process as the students argued that ribosome is the organelle that initiates the process. As a result, students tended to describe that an enzyme was synthesised in ribosomes instead of the nucleus. The role of the nucleus appeared unclear to the students. The role of mitochondrion also remained abstract as the majority of students assumed that mitochondrion was not required in the enzyme synthesising process mostly because the mitochondrion only generated energy for daily life activities and not for cellular activities.

In investigating the relationship between the substrate and enzyme concentrations towards enzyme reaction, few students were unable to correlate the rate of reaction to the property of enzyme. Students argued that enzyme reaction will decrease if more substrates are added because enzymes are being occupied. However, enzymes can be re-used once the substrate is broken down into a product. Hence, the rate of reaction will remain the same. Likewise, the rate of reaction will remain the same even with higher enzyme concentration (with the same amount of substrate) as the substrate concentration becomes a limiting factor.

Based on the analysis of students' incoherencies the activities planned in the Living Cell Tool were tasks 3 and 6 in the third topic (Refer Appendix E). An example of the task (task 6) is shown in Figure 4.6.

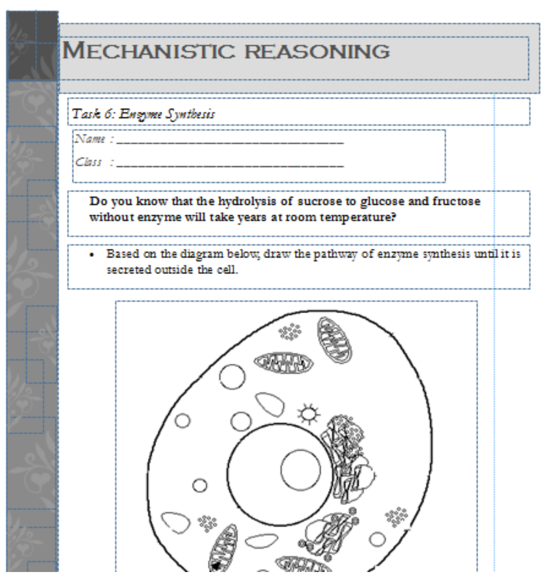



*Figure 4.6.* An example of the task (task 6) which is prepared based on students' incoherencies

**Cell Division**

Table 4.12 indicates the incoherencies that were identified in students' understanding. Followed by the Table 4.13 was the explanation for the incoherencies.

Table 4.13

*Incoherencies in Students' Understanding*

| Item | Content | The Incoherencies |
|---|---|---|
| | Organelle and cell division | |
| **1** | Organelle and cell division | Only nucleus is involved in cell division because cell division does not require energy |
| **2** | Organelle and cell cycle | New organelles are synthesised in an original cell and transferred to a new cells (desired content knowledge) because the genetic information in the nucleus in a new cell will synthesise new organelles.<br><br>New organelle is synthesised in a new cell by nucleus because nucleus contains genetic information. |
| | Chromosome | |
| **5** | Chromosome labelling | M is chromatid while N are sister chromatids (desired content knowledge) because sister chromatids are used in mitosis.<br>M is chromatid while N is a homologous chromosome because homologous chromosomes are made up of 2 sister chromatids. |
| **11** | Chromosome labelling | S is a sister chromatid while T are homologous chromosomes (desired content knowledge) because sister chromatids consist of 2 chromatids while homologous chromosomes consist of 2 sister chromatids |
| | Mitosis | |
| **3** | Importance of mitosis | Produces gamete is not the importance of mitosis (desired content knowledge) because zygote undergoes meiosis to form new cells |
| **4** | Cell cycle and types of division | Phase J occurs before mitosis not meiosis because interphase only occurs before mitosis<br>Phase J in mitosis and meiosis is different because mitosis and meiosis are different processes. |
| **8** | Types of cell and mitosis | Cells in fallopian tube do not undergo mitosis process because it produces gamete which requires meiosis. |
| **10** | Tumours | Tumours are not caused by the failure of chromosomes to separate (desired content knowledge) because the failure will cause the tumours to spread. |

Table 4.13 (Continued)

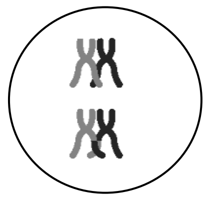
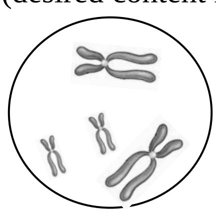
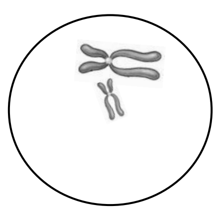
| | | |
|---|---|---|
| | Meiosis | |
| **12** | Importance of having haploid cell | To restore the number of chromosomes (desired content knowledge) because when a haploid cell fuses with another haploid cell it will produce variation. |
| **13** | Meiosis process | DNA replication only occurs once in meiosis (desired content knowledge) because DNA replication occurs during prophase I and II.<br>Interphase occurs twice in meiosis because interphase only occurs during meiosis I. |
| **14** | Metaphase in meiosis | Metaphase I<br><br>Because crossing over occurs during metaphase I but do not occur during metaphase II<br><br>Answers A and C do not illustrate the process of crossing over |
| **15** | Mitosis and meiosis | Process B is mitosis (desired content knowledge) because meiosis takes place in a fallopian tube where a zygote is implanted. |
| **21** | Mitosis and meiosis in plants | Plants form through meiosis and mitosis (desired content knowledge) because plants have gametes which are formed through meiosis only. |
| | Chromosomal number and genetic constitution | |
| **6** | Chromosomal number and mitosis | A. (desired content knowledge)<br><br>Because the cell undergoes mitosis to form 2 daughter cells<br>C.<br><br>Because the cell undergoes mitosis to form 2 daughter cells. |
| **7** | Genetic and mitosis | The genetic information in a skin cell and the original cell will be the same (desired content knowledge) because they are same types of cells. |

Table 4.13 (Continued)

| | | |
|---|---|---|
| **16** | Chromosomal number in plants | The chromosomal number for seed is 24 if the chromosomal number of the plant is 24 (desired content knowledge) because seed undergoes meiosis.<br>The chromosomal number for stigma is 12 if the chromosomal number of the plant is 24 because stigma produced ovum which undergoes meiosis |
| **17** | Types of cell and chromosomal number | The egg cell divides to produce cells with 2 chromosomes each (desired content knowledge) because meiosis form diploid cell.<br>The egg cell divides to produce cells with 4 chromosomes each because meiosis forms 4 daughter cells |
| **18** | Types of cell and chromosomal number | The genetic information of an egg cell and the original cell is different (desired content knowledge) because they are different types of cell.<br>The genetic information of an egg cell and the original cell is similar (desired content knowledge) because they are same types of cell. |
| **20** | Types of cell and chromosomal number | The number of chromosomes after the fusion of sperm and ovum is 8 because each gamete consists of 4 chromosomes. |
| **22** | Types of cell and genetic | The genetic information of a cheek cell and a nerve cell is different because they are different types of cell. |
| **23** | Types of cell and genetic | The genetic information of a cheek cell and a sperm cell (desired content knowledge) is different because they are different types of cell. |
| **24** | Replication in cell cycle | Replication process does not occur during S phase because it involves crossing over. |

Based on Table 4.13, students appeared to have more incoherencies in their reasoning for this topic as compared to the previous four topics (items 2, 3, 5, 6, 7, 10, 11, 12, 13, 14, 16, 17, 18, 21 and 23). While investigating the organelles that were involved in cell division (item 1 and 2), findings were consistent with the previous incoherency tests that revealed the complication in understanding the function of the mitochondria and nucleus. Firstly, students only perceived the role of the nucleus during the process. Students' reasoning also revealed that they were unclear about the exact function of the nucleus as they believed that new organelles were synthesised by a nucleus in a new cell because it has all the genetic information. The fact is some organelles are actually able to synthesise new organelles by their own during the $G_1$ phase of the cell cycle. Secondly, the function of the mitochondrion remained unclear for the students as they believed that mitochondrion was not required during cell division.

Students showed no problem in labelling the types of chromosomes (items 5 and 11). Nonetheless, students did not understand the underlying reason of labelling the chromosomes in such a way. In probing students' understanding deeper about the structure of sister chromatids and homologous chromosomes, students' reasoning suggested a surface understanding by relating the types of chromosomes with the physical appearance of the structure or processes rather than understanding that sister chromatids are actually two identical copies of chromosome whereas homologous chromosomes are chromosomes of the same length and same position of genes.

An inconsistency emerged in item 3 as the reason selected by students was contradicted to their content knowledge. Students knew that producing gamete is not the importance of mitosis (desired content knowledge), however, the reason chosen to support the statement was that zygote undergoes meiosis to form new cells. There were two incoherencies found based on this finding: (i) students were unsure about the importance of mitosis – either producing gamete or forming new cells in zygote, (ii) zygote undergoes mitosis to form new cells not meiosis. Clearly, students believed that both statements were correct but the reason did not match the content knowledge. Besides that, students also had partial understanding of the relationship between interphase and cell division (mitosis and meiosis)(item 4). Part of the students believed interphase only occurs in mitosis and not meiosis. Even if interphase does occur in meiosis, the process will be different. This might be due to compartmentalisation in learning as interphase was only introduced before the mitosis process. The replication process during interphase was also not well understood by the students (item 24) as students perceived replication was similar to crossing over which does not take place during interphase.

It is apparent that students did not fully comprehend the types of cell division in different organs. This can be seen in item 8 where students believed that the cells in a fallopian tube divided by meiosis as it produced gamete. This finding was aligned with item 15 where students had to distinguish the division process in a human life cycle. A number of students selected “the cells in zygote undergo meiosis because it is still in fallopian tube” as their reason. Students assumed that the cells in reproductive organs divide by meiosis as they involved in production and delivery of gametes. A similar situation occurred in plants where students thought that stigma undergoes meiosis because it contains gamete (item 16).

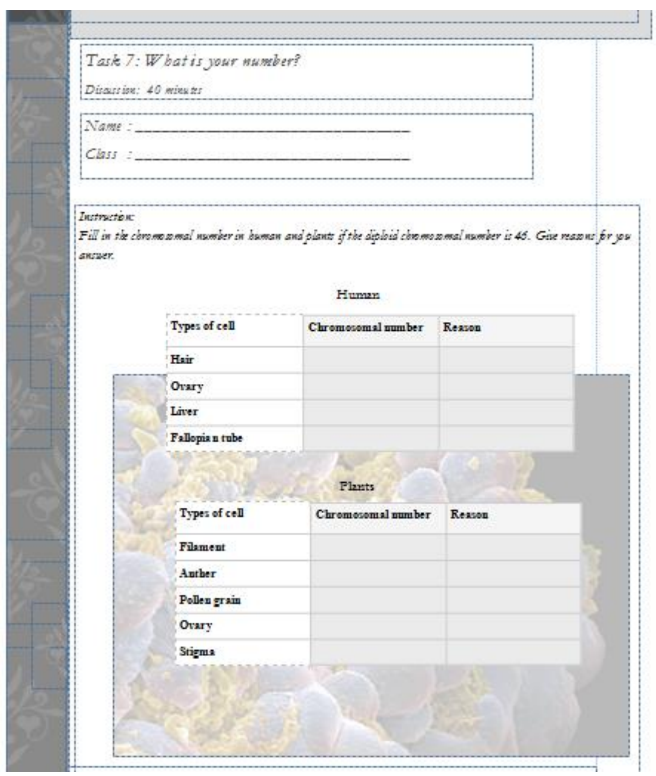
The application of mitosis was well-understood by students especially in cloning. Students were able to explain the offspring form was based on the nucleus it was derived from and not the ovum. However, the understanding of the formation of cancer was weak as the analysis in students’ reasoning showed contradiction in item 10. Students understood that tumours were not caused by the chromosomes that failed to separate, but they claimed that the failure of separation will cause the tumours to spread. Tumours will spread because they have the capacity of metastasise.

Meiosis was much more difficult to be understood by the students as compared to mitosis (items 12- 15). Although students were able to pinpoint that producing haploid cell in meiosis is important to restore the diploid number of chromosomes, the reason selected were two haploid cells fused together will give rise to variation instead of a diploid cell which will only form through the fusion of two haploid cells. The incoherency suggested that students were unable to grasp the meaning of restoring the diploid chromosomal number. With the problem in understanding cell replication and interphase (as described in the above section), students were unable to distinguish especially replication and interphase should occur once or twice in meiosis (item 13). Some students believed that DNA replication occurs during prophase I and II in meiosis. The fact is DNA replication only occurs once in meiosis as the process takes place in interphase which happens before prophase I of meiosis. Incoherency in understanding of the phases in meiosis was also indicated in item 14. The incoherencies (based on Table 4.13) revealed that the word ‘crossing over’ was deep rooted in students’ minds that they believed every phase in meiosis was related to crossing over. However, crossing over only occurs in prophase I of meiosis. In comparing the meiosis and mitosis process in plants, students showed uncertainty about the cell division that happens in plants (item 21). Although they selected that both divisions can take place, the reason opted for was plants have gametes which reproduce through meiosis only. Students did not recognise vegetative propagation as a form of reproduction which is produced through mitosis.

A lot of items were concentrated on the relation of cell division to the genetics constitution or number of chromosomes produced. Overall analysis showed students were able to select the desired genetic constitution or number of chromosomes in a new cell. However, the reason selected by the students indicated otherwise. For example, item 17 revealed, firstly, haploid and diploid cells were not well comprehended by students as they assumed that egg cells will produce cells with 2 chromosomes because meiosis forms diploid cells. Secondly, students thought that the number of chromosomes is similar to daughter cells. As a result, they selected 4 chromosomes in the egg cell with the reason meiosis produces 4 daughter cells. Likewise, in item 20 where students chose the chromosomal number which arose from the fusion of sperm and ovum will be 8 because each gamete consists of 4 chromosomes. Sperms and ova are formed through meiosis with a chromosomal number of 2. Thus, the fusion of both gametes will produce cells with a chromosomal number of 4.

Students often related the genetic information with the type of cell rather than the process in cell division. Students thought that the genetic information will be identical or different in mitosis mostly because the type of cell is similar or different (such as item 18, 22 and 23). However, the genetic constitution of a cell does not depend on the type of cell. The genetic information of somatic cells will be the same as they carry out mitosis which results in genetic identical cells. On the contrary, gametes' genetic information is different due to crossing over in the meiosis process.  Again, students showed shallow understanding by examining the appearance of the cell rather than the underlying concept.

Based on the analysis of students' incoherencies the activities planned in the Living Cell Tool were tasks 4, 6 and 7 in cell division (Refer Appendix E). An example of the task (task 7) is shown in Figure 4.7.



*Task 7: What is your number?*

*Discussion: 40 minutes*

*Name :* ______________________________

*Class :* ______________________________

*Instruction:*

*Fill in the chromosomal number in human and plants if the diploid chromosomal number is 46. Give reasons for you answer.*

Human

| Types of cell | Chromosomal number | Reason |
|---|---|---|
| Hair | | |
| Ovary | | |
| Liver | | |
| Fallopian tube | | |

Plants

| Types of cell | Chromosomal number | Reason |
|---|---|---|
| Filament | | |
| Anther | | |
| Pollen grain | | |
| Ovary | | |
| Stigma | | |

*Figure 4.7.* An example of the task (task 7) which is prepared based on students' incoherencies

The final version of the Living Cell Tool is given in Appendix E.

## Actual Study

The actual study was to explore students' mechanistic reasoning using the Living Cell Tool. The Incoherency tests were carried out in October 2010 and the analysed data was utilized to modify and consolidate the Living Cell Tool so that the tool was finalised to be utilised in January 2011. The overall time frame for the pre-study phase, pilot study and actual study are illustrated in Figure 4.8. The details of the actual study will now be discussed.

### Students' Mechanistic Reasoning

This study is an exploratory study which employed the qualitative data collection method. This study explores high and low achieving students' mechanistic reasoning for the Theory of Cell. This present study may provide insight to educators on how high and low achieving students might generate their mechanistic reasoning, their progression over time as well as the representations of their mechanistic reasoning.

#### Selection of participants

Form Four Pure Science students (n=40) from one of the government secondary schools were selected for the study. The reason for selecting only one class from one government secondary school was because the biological processes (topics 2-5 of Biology) which were investigated in this study were taught simultaneously in most secondary schools in Malaysia. Therefore, it will be difficult to investigate more than one school.

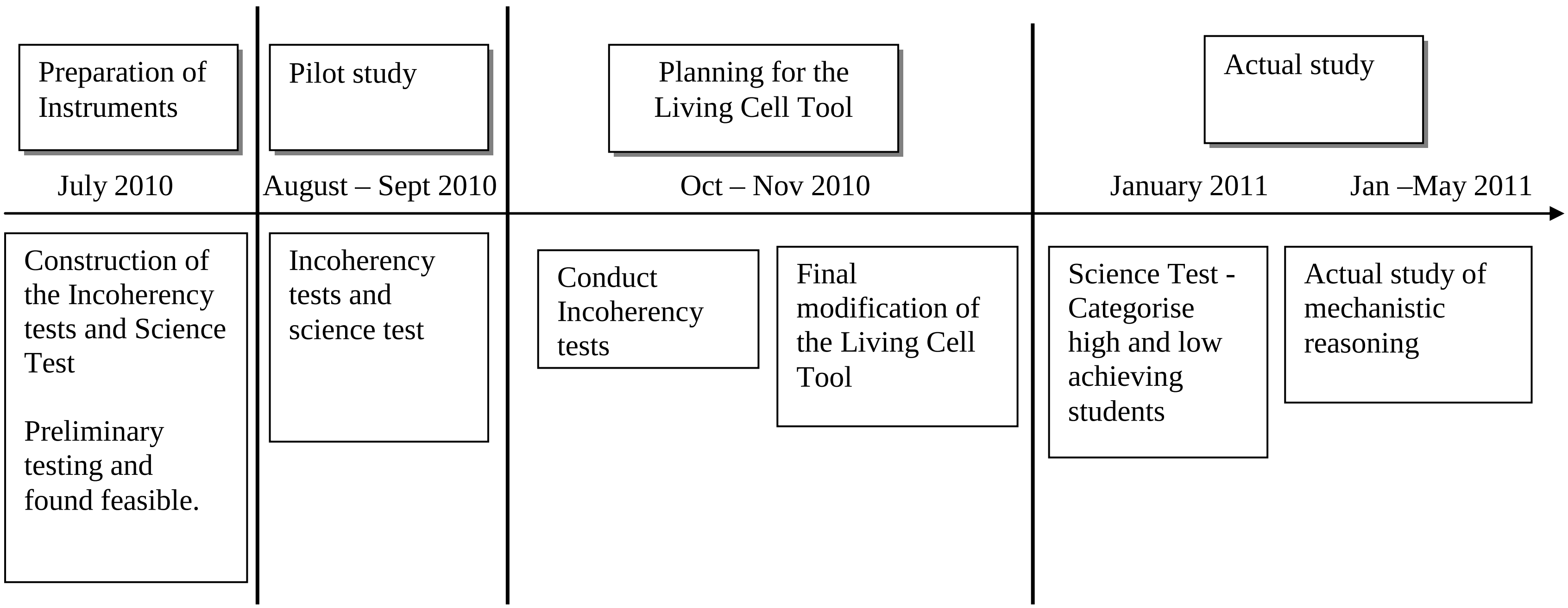



*Figure 4.8.* Time frames for preparation of instruments, pilot study, planning for the Living Cell Tool and actual study

The students in the sample were also from a pure science background, and biology is one of the compulsory subjects in their curriculum. As the study intended to investigate high achieving and low achieving Form Four science students' mechanistic reasoning, the students were first categorised based on the science test which had already been constructed and pilot tested during Phase I. The science test was administered to the Form Four students at the beginning of the year 2011 before the investigation of mechanistic reasoning began by utilising the Living cell Tool. The marks from the science test were tabulated using an accepted standardised public examination scale (Malaysian Certificate of Examination). The categorisation of the participants according to two different achievement levels is shown in Table 4.14.

Table 4.14

*Categorisation of Participants According to the Two Different Achievement Levels Using a Standardised Examination Scale.*

| **Standardized** | **Scale** | **Achievement Levels (Based on Science Test)** | **Number of Participants** |
|---|---|---|---|
| A | 80 – 100 | High | 4 |
| B | 41 – 79 | Average | 26 |
| C and below | 10 – 40 | Low | 8 |
| | | Total Number of Participants | 38 |

In Table 4.14 above, 8 out of 38 students were categorized as low science achievers (L), 26 of them were categorized as average science achievers and the remaining 4 of them were categorized as high science achievers (H). However, two of the low achieving students dropped out from the study due to high absenteeism. Hence, only 6 of the low achieving students' data were analysed.

Although the focus of the study was mainly on high achieving and low achieving science students, the categorisation was only known to the researcher and all students were treated alike. Data was collected from the average students so as not to create any disruption or negative perceptions among the students.

## Procedures for the Data Collection Using the Living Cell Tool

The investigation of students' mechanistic reasoning employed a qualitative method of data collection. Several qualitative methods of data collection were utilised which were students' written task in the Living Cell Tool, classroom discussion observation, researcher's observation note and interviews. As stated in the previous section, the achievement levels of the students were categorised using the science test before using the tool. Since the tool was constructed not only based on students' common incoherencies uncovered in relation to the Malaysian curriculum specification of Biology, the usage of the tool was within a normal classroom lesson. Now the infusion of the tool will be discussed. This is followed by the description of the data collection method.

### Infusion of Mechanistic Reasoning

Lewis and Kattmann (2004) stated that students who failed to recognise the mechanisms (mechanistic reasoning) in the process consequently had little awareness of the relationship across biological processes. This explains why many students failed to acquire a coherent conceptual understanding of the cell as a basic unit of organism (Dreyfus & Jungwrith, 1988, 1989; Flores, 2003). Thus, in order to prepare a tool to infuse mechanistic reasoning, students' incoherencies were identified based on the incoherency tests as well as existing literature review which were discussed in the planning of the Living Cell Tool tasks section. The 'infusion' of the reasoning approach by using worksheet or tasks has also been adopted elsewhere (Davies, 2006; Reed & Kromkey, 2001; Melville Jones, 1999)

The researcher herself carried out the activities and the tasks in the Living Cell Tool since it was aligned with the four chapters of Form Four Biology in the Curriculum specification. Minimum teaching of the content for the topics was carried out as the tool encompassed the content necessary to be learned by the students. Therefore, the tool was used during normal classroom lessons. The subject teacher was in agreement. The researcher was allowed to enter the normal classroom lesson on Tuesday, Thursday and Friday for that particular class selected. To minimise the biasness of the study, observations by the subject teacher was necessary (Fraenkel & Wallen, 2007). Lessons conducted in the classroom were also videotaped and were peer reviewed by two experienced Ph.D researchers to increase the validity and reliability of the data. The observation protocol by the subject teacher is given in Appendix F.

The tool acted as an instrument to infuse students' mechanistic reasoning and also to collect students' mechanistic reasoning data. The researcher followed the tasks in the tool for the classroom activities. Table 4.15 shows the time line for the infusion and data collection of mechanistic reasoning by using the Living Cell Tool spanning over different months.

Table 4.15

*Time Line for Infusion and Data Collection of Mechanistic Reasoning by Using the Living Cell Tool*

| **Infusion and data collection (month)** | **Topic in the Living Cell Tool** |
|---|---|
| January 3 – 7, 2011 | Introduction |
| January 10 – 28, 2011 | Cell structure and cell organisation (Topic 1) |
| February 31 – 6, 2011 | Holidays |
| February 7 – 28, 2011 | Movement of substances across the plasma membrane (Topic 2) |
| March 7 – 11, 2011 | Exam |
| March 12 – 20, 2011 | Holidays |
| March 21 – 31, 2011 | Chemical composition of cell (Topic 3) |
| April 1 – 15, 2011 | Chemical composition of cell (Topic 3) |

Table 4.15 (Continued)

| | |
|---|---|
| April 16 – May 13, 2011 | Cell division (Topic 4) |
| May 14 – 27, 2011 | Exam |

Some tasks in the tool required group work while some did not. The students were either working in groups or individually to carry out the tasks given. As students carried out the tasks, the discussions within a group or students' presentations were audio and video taped to keep track of students' mechanistic reasoning. Individual tasks of students' written answers were also collected and analysed for their mechanistic reasoning. Therefore, the researcher would like to emphasise the usage of the tool is not solely for infusion of mechanistic reasoning but also a crucial tool to collect data in relation to students' mechanistic reasoning.

**Qualitative Data Collection of Mechanistic Reasoning**

As mentioned earlier, the investigation of students' mechanistic reasoning employed qualitative data collection techniques. Several qualitative data collection techniques were utilised which were students' written tasks in the Living Cell Tool, classroom discussion observations, researcher's observation notes and interviews. The outlines of the ways to collect qualitative data and the practical considerations that researchers need to take into account as they implement these strategies were referred to James, Milenkiewicz and Bucknam (2007). Table 4.16 shows the purpose and the method utilised in this present study.

Table 4.16

*Purpose and Method Utilised in this Present Study*

| **Method** | **Purpose** |
|---|---|
| Data collected during the event(s) being studied | |
| Observations: note taking during infusion and discussion of mechanistic reasoning in a normal classroom lesson setting. | • Collected over a period of time which is five months in this present study among high and low achieving students' mechanistic reasoning.<br>• This could increase the possibility of reliable results (James, 2007). Accuracy may be helped by voice or video recording which was also employed in this study. Data was peer reviewed as well as by the expert panel to identify any misleading or skewed questions during the infusion. Improvement in teaching was made based on the feedback. |
| Students' written task in the Living Cell Tool | • Collected over time to capture students' mechanistic reasoning from task to task |
| Data collected directly in words from people | |
| Interviews: Semi-structure interviews | • Reveal and clarify information about students' written mechanistic reasoning in the Living Cell Tool. |
| Data collected throughout a process | |
| Field notes*:* written explanations or data taken by observers at a single event | • Capturing interactions of students' mechanistic reasoning. |

As the study progressed from January to May, 2012 there were two types of main qualitative evidence collected. First, students' written answers that reflected their mechanistic reasoning in the Living Cell Tool. Second, the researcher also collected observational data about students' mechanistic reasoning during classroom discussions. Thus, an observation protocol was developed which is shown in Appendix F.

Tessier (2012) suggested that field notes, transcripts and tape recordings should be used together to enhance the quality of data management in qualitative data collection. Field notes are important in capturing initial thoughts of the research. Thus, in this present study, the researcher also utilised field notes as part of the qualitative data collection as support. However, filed notes had some reliability issues because of their inability to "replay" the event and this can be overcome by tape recording and, more specifically, the use of transcripts (Tessier, 2012). Therefore, in this present research, the researcher audio and video taped every lesson when the research was conducted besides writing field notes. These field notes were also cross checked with the observation notes from the video recording to reduce the researcher's biasness. The video recording was also reviewed by the expert panel to ensure that the Hawthorne effect can be reduced by giving suggestions to improve as well as to identify misleading questions asked by the researcher. In addition, observation from the subject teacher also contributed to ensure that the researcher bias is lessened and that the researcher did not mislead the students in collecting students' mechanistic reasoning data.

The researcher utilised semi-structured interviews to clarify the mechanistic reasoning given by individual students while carrying out the tasks in the Living Cell Tool to avoid any misinterpretation of the mechanistic reasoning put forward. However, not all students were interviewed. Only those whose written answers in the Living Cell Tool were vague or unclear, were interviewed to gather further data in the subjects own words so that the researcher could develop insight on how students answered the questions in the tasks given. Besides that, the interviews helped to support the data obtained from the task.

The researcher developed questions through an iterative initial process and tested it out to ensure the questions were understood by the students. After the testing, a short list of questions was determined. The interview protocol is shown in Appendix G. The interview session as suggested by James (2007) with the students was set to not more than 60 minutes to avoid participant fatigue. In addition, a tape recorder was used to capture students' exact words with their consent.

The data collected from different types of sources were analysed. A set of data collection source including an example of interview transcripts, classroom discussion transcripts, subject teacher observation notes and researcher's observation notes are shown in Appendix H. The analysis and the uncovering of students' mechanistic reasoning patterns from the sources will be discussed in detail due to its complexity in the next chapter which is Chapter 5 due to its complexity. Figure 4.9 indicates the overall design of the study while Figure 4.10 indicates the overall procedure of the study.

## Validity and Reliability

Reliability can be thought of as the trustworthiness of the procedures and data generated (Stiles, 1993). It is concerned with the extent to which the results of a study or a measure are repeatable in different circumstances (Bryman, 2001). Thus, the findings must be confirmed by revisiting data in different circumstances (Robert, Priest, Traynor, 2006). For example, to overcome any researcher bias in the interpretation of the data and as an auditing measure, interview data may be sent to an independent researcher to verify how much agreement there is about the findings and the analysis. Thus, the analysis in this present study was peer reviewed by a qualitative analysis expert from one of the local universities and peers (two Ph.D researchers who have experience in qualitative study). In addition, the analytical steps in this study were presented to two international researchers (Appendix N) as well as submitted to an international journal. The feedback from them were utilised to enhance the analytical steps put forward. Another method to increase reliability is to utilise tape-recorded observations or interviews (Peräkylä, 1997). Therefore, both audio and video recording were utilised during interviews and observations. Intensive engagement of data can help to improve the reliability by moving forward and backward between the data and the interpretation of it (Robert, Priest, Traynor, 2006). Therefore, students' verbatim examples either in interviews, observations or written tasks were adopted to increase the reliability and readability. How audio and video recording could increase the reliability was discussed in the precious section.

Validity is accessed on how well the research tools measure the underlying phenomenon (Punch, 1998). A potential difficulty in achieving validity is researcher biasness. Researchers who are familiar with the field may overlook certain nuances and ambiguous data because of their implicit understanding of the research setting (Robert, Priest, Traynor, 2006). Thus, it is suggested by Robert, Priest, Traynor (2006) that the researcher can be reduced by respondent validation. This refers to the practice when researchers share interpretations and theorise with the research participants, who can check, amend and provide feedback as to whether they are recognisable accounts consistent with their experience (Bryman, 2001). In this present study, the transcription of the interviews, classroom observations as well as students written tasks in the Living Cell Tool were sometimes shared with participants to ensure the interpretation of their mechanistic reasoning was correctly described.

Prolonged engagement in the research site is another way to improve the validity of the research (Robert, Priest, Traynor, 2006) which was also employed in this study as it took five months of engagement in the research site. Regular supervision and peer review on the analysis and findings by the researchers will also enhance the validity of the research which was also utilised in this present study. Researchers claim that it is impossible to be completely objective or detached in the research process (Guba and Lincoln, 1981; Stiles, 1993). However, efforts can be made to minimise the error and biasness in order to produce a valid and reliable research.

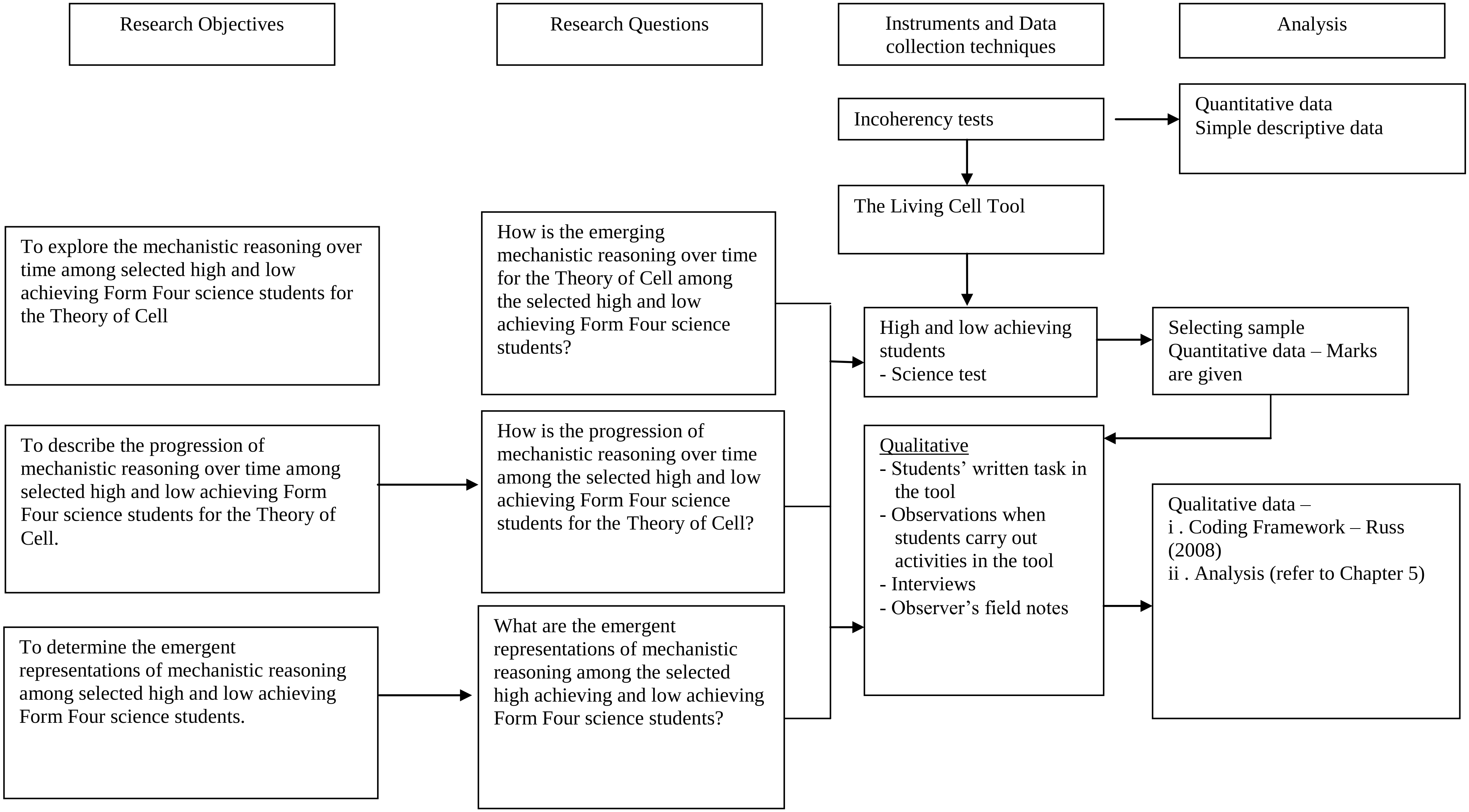



*Figure 4.9.* Design of the study

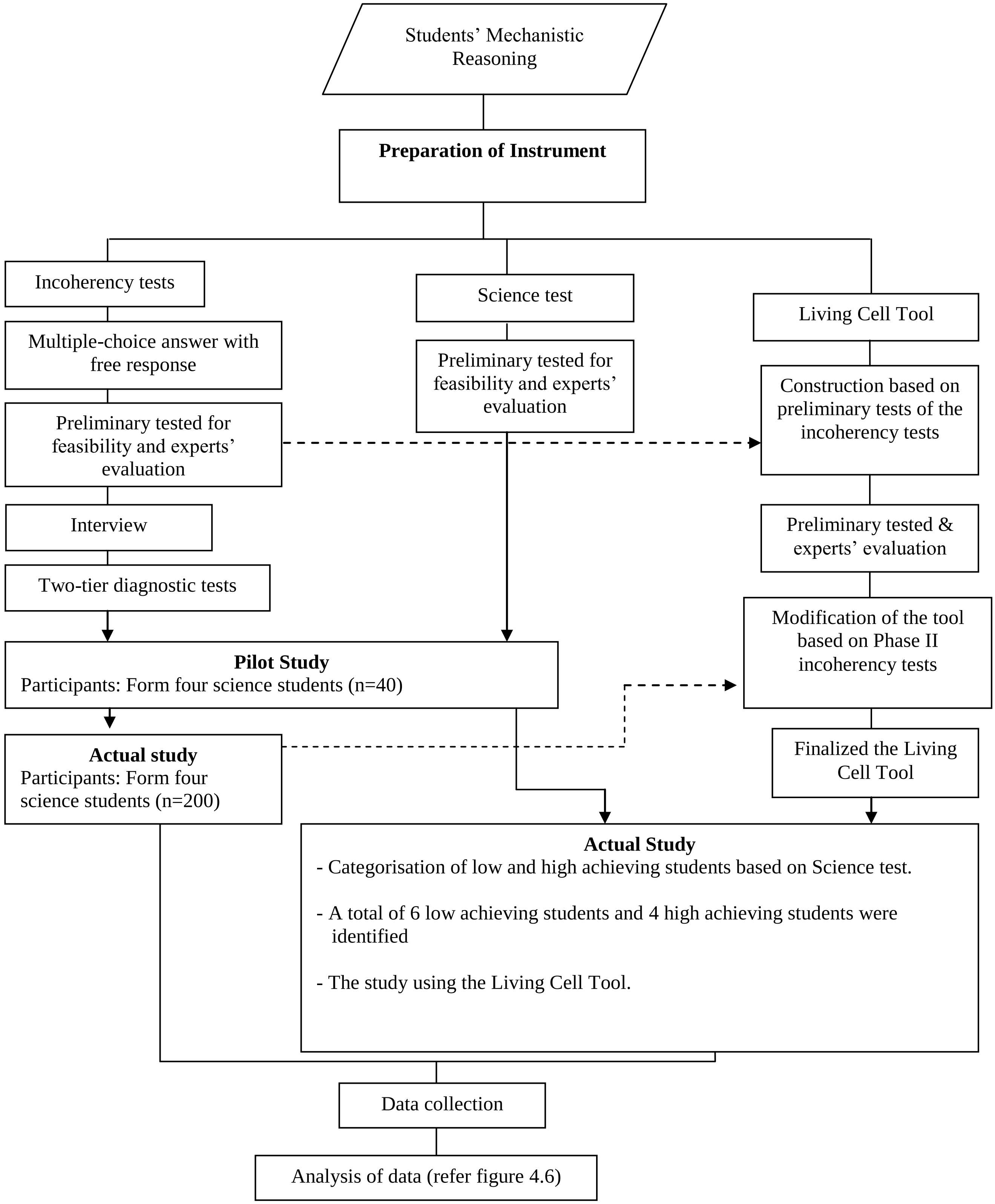



*Figure 4.10.* Overall Procedure of the Study