CHAPTER 2

REVIEW OF LITERATURE

Introduction

Mechanistic reasoning involves looking inside the ‘black box’, and relies on underlying mechanisms that relate to cause and effect (Russ et. al., 2008). The term ‘mechanisms’ is widely used in philosophical literature in discovering several processes that take place in one organism (Machamer, Darden & Craver, 2000). In recent times, mechanistic reasoning has gained much attention from medical sciences as this reasoning involves an inferential chain linking of the intervention and outcome (Howick, Glasziou, & Aronson, 2010). Hence, mechanistic reasoning is crucial in developing coherent understanding.

However, numerous comprehension difficulties have been identified even for the basic concepts which are related to the Theory of Cell. This will be discussed in the first part of the following sections. A more detailed explanation of the discovery of mechanistic reasoning will be discussed in the second section. This will be followed by the strategies of mechanistic reasoning as well as the value of mechanistic reasoning in developing coherent understanding.

This present research mainly focuses on two groups of students which are high and low achieving students’ mechanistic reasoning. Is it true that it is not really appropriate to assist low achieving students cultivate higher order thinking skills such as mechanistic reasoning? This will be argued out based on the existing literature. Lastly, the methodology aspects of mechanistic reasoning in previous studies will be discussed.

The Cell as Part of the Living World

The living world appears as an organized hierarchical structure in which the entities at one level are compounded into new entities in the next level, i.e. molecules into cells, cells into tissues, tissues into organ and organ into functional systems. For a full understanding of living phenomena, every level should be studied. It can be reasoned that the living world is not just a combination of its components; but rather, its function relies entirely on mutual interrelations, interactions and interdependence among these components (Mayr, 1997). Comprehension of the living world requires the interconnection of knowledge at many different levels and of the relationships within those levels. In other words, an understanding is required not only of the components associated with a particular entity, but also those derived from the interrelations among entities at the same or different levels (Lin & Hu, 2003).

Since the cell is the basic structural and functional unit of every living organism, teaching basic life functions in a meaningful way involves dealing with the relations between structures and functions at all organizational levels, including the cellular level (Douvdevany et al., 1997). A basic understanding of the functioning of the cell is essential for an understanding of the functioning of the cellular organism. This is why understanding the cell topic is central to understanding some of the most important biological phenomena, and offers an opportunity to examine the cellular explanation of those phenomena (Cohen &Yarden, 2009)

Numerous misconceptions and comprehension difficulties with regard to the cell have been identified (Dreyfus & Jungwirth 1988, 1989; Flores, 2003).The Cell as a theme of study has been characterized as difficult to understand by the students at different educational levels. These conceptual problems range from the understanding of the cell as an autonomous organism and the functions it performs, to difficulties in its spatial and metrical representations. This results in confusion in the understanding between cells, atoms and molecules. In particular, the establishment of relationships between cell structure and their functions are especially complex for students who are not able to integrate them into an overall picture. Chi et al. (1994) report on students’ difficulties in describing the connections among local and system-wide features of the human circulatory system. Comprehension problems appear across all levels from general to cellular. The most significant are:

i. The articulation between the structural unit of cells and multicellular organisms
ii. The functioning of the cell membrane
iii. Confusion between photosynthesis and respiration
iv. The classification of organisms as simple and complex and the incorrect inferences made about the cell
v. Confusion between mitosis and meiosis
vi. The differentiation of concepts such as the genetic code, chromosome, DNA, etc.
vii. Structural organisation and external morphological differences are transferred to cell processes
viii. Problems with recognizing a variety of cell forms and size.

Kiboss et al. (2004), in his study, stated that a considerable number of secondary schools pupils hold inadequate understanding of the Theory of Cell and associated underlying concepts such as mitosis, meiosis, chromosomes and chromatids. Lazarowitz and Lieb (2006) identified several topics related to the Theory of Cell that are “difficult” for students’ learning. The topics include: (1) water transport in organisms (2) osmosis and osmoregulation; (3) chemistry of respiration and photosynthesis; (4) energy cycle (ATP/ADP); (5) cell respiration; (6) protein synthesis; (7) mitosis and meiosis; (8) enzyme structure and function; (9) chromosome theory and heredity; and (10) Mendel’s law of genetics and multiple alleles.

Riemeier and Gropengieβer (2008), similarly, stated some problems in learning cell biology:

i. Confusion about the term such as cell, cell wall, cell membrane, gene, chromosomes, allele, etc.
ii. Problems in understanding the different levels of organisation of multi-cellular organisms.
iii. Problems in understanding cell processes such as mitosis or DNA replication.

General conceptions of Biological Processes Related to the Theory of Cell

A cell is the basic unit of life. Hence, it is crucial to understand the cell in Biology before proceeding to any biological processes. Students recognise that the cell is the structural unit in which organisms are formed. However, difficulties in learning the Theory of Cell hinder students’ understanding of other biological processes such as osmosis and diffusion, mitosis and meiosis and photosynthesis. Students found it complicated to understand the cell’s internal structure whereby some organelles have unknown functions such as cell membrane and golgi apparatus (Flores, 2003). The anthropomorphic view is highly generalized in learning the Theory of Cell and it is shown in different subjects (Flores, 2003). For example, respiration in cells need oxygen in the same way as humans do. Another expression of this view is that cells take what they need from the environment and a cell “makes decisions” about its requirements. These ideas are reflected mainly in the processes of osmosis and phagocytosis where the cell ‘knows’ what it must allow to go through or take from the environment. In the same sense is the students’ idea that ‘cell reproduction originates in two cells’, which has as the main analogy the source of sexual reproduction in animals. Another idea is that ‘animal and plant cell processes are different, therefore differences between multicellular organisms are applied to cells’, for example, mitosis and asexual reproduction only take place in plant cells and they conceive plant respiration as anaerobic.

Movement of Substances across the Plasma Membrane

Diffusion and osmosis are fundamental processes for living organisms as both explain the exchange of substances between cells and the environment. Hence, these concepts are introduced in the initial stages of most Biology textbooks after the Theory of Cell as these concepts deal with cellular structure and functioning. Diffusion is the primary method of short-distance transport in a cell and cellular systems. An understanding of osmosis is the key to understanding water intake by plants, water balance in land and aquatic creatures, turgor pressure in plants and transport in living organisms (Odom & Barrow, 1995). Diffusion and osmosis were studied for two reasons: (i) they are important processes in understanding how biological systems function and (ii) both processes have proven difficult to teach. One difficulty is that formal reasoning is required to understand diffusion especially osmosis. Another difficulty is making sense of the technical concepts such as solution, solvent, semi-permeability and net movement. The third one is that there is often confusion between vernacular and scientific usage of terms such as pressure, concentration and movement (Christianson and Fisher, 1999). Students at all grade levels, including college students, have difficulty in understanding some of the fundamental concepts of diffusion and osmosis, and many of them have misconceptions about these processes throughout their lives (Marvel & Kepler, 2009).

Many students are unable to state that water will move into the cell if it is placed in a hypotonic solution and out of a cell if it is placed in a hypertonic solution (Odom &

Barrow, 2007). It is important for students to be exposed to the concept of osmosis and diffusion. This is because these concepts are used to explain why an animal cell, like erythrocytes, which are placed in hypotonic solutions, will burst. As in plant cells, these concepts are vital in explaining why a plant maintains its freshness. Lazarowitz and Lieb (2006) stated that students do not have a clear knowledge about diffusion. An example was given in a study conducted by Wang (2007). When students were asked what caused the water flows into plants, more than one third of the students said that plants have root hairs to absorb the water from soil through capillary action instead of osmosis.

A common test for the concept of diffusion is to explain why when a blue dye is placed in a container of clean water, it will evenly distribute throughout the water. According to Odom and Barrow (1995), some of the students answered that the dye separates into smaller particles and spreads out. When the concept of diffusion was applied to the body cell, students failed to exhibit a coherent linkage on how the glucose molecules moved across the capillary into cells in muscle tissues. Some of the students explained that "the glucose mixes in the blood in the capillary" or "the glucose molecules travel down the centre tube and mixes with the blood and from there it passes through the capillary wall and into the body cells in muscle tissues" (Panizzon, 2003). Students were unsuccessful in understanding diffusion which occurs in body cells because they had learnt the Theory of Cell and the diffusion concepts separately and not in relation to one another.

Cell Division

The topic of cell division has consistently been given prominence difficult to topics learnt by pupils and widespread concept confusion has been documented (Lewis, et al., 2000c; Marbach-Ad & Stavy, 2001; Lewis & Kattmann, 2004; Saka et al., 2006). Friendenreich, Duncan and Shea (2012) mentioned that the domain of genetics is particularly difficult to teach and learn due to the many unfamiliar cellular and molecular components and processes involved. One of the major processes that is related to genetics domain is cell division. Reasoning in genetics becomes even more challenging as it requires integration knowledge across multiple levels of biological organisation (such as gene, protein, cells, tissues and organs) and linking multiple concepts (Friendereich et. al.).

A study conducted by Lewis et al. (2000a) suggested the widespread uncertainty about the process and products of mitosis. For example, students were asked "How many chromosomes would be found in the new skin cells?" Over half the students answered correctly- "chromosomes will remain the same". However, the justifications for this were not always compatible with the scientific view. Over one third of the students who said the chromosomes will remain the same because the cells were of the same type instead of mentioning the significance of mitosis. While some students were unable to distinguish between cells and chromosome, some students suggested that new cells had more chromosomes because they were young and old chromosomes would eventually die. Lewis et al. (2000b) also pointed out that some students giving justification made no distinction between meiosis and mitosis by giving the answer that all cell divisions resulted in an equal sharing of chromosomes. Some students said that plants only carried out mitosis not meiosis because the plants did not have sexual reproduction and plants grew from roots, therefore they do not mate together. This is supported by the study carried out by Marbach-Ad and Stavy (2000) that students were confused about meiosis, mitosis and crossing over. For instance, a student answered: "The DNA duplicates and divides equally, as in meiosis, so the strands are the same." Another student said: "The DNA in the bacterial cell is not identical to the DNA that was in a mother cell, because there was crossing over before the division". It is obvious that students' scientific understanding of mitosis and meiosis is inadequate especially for plants.

In investigating students' understanding of the genetic relationship between cells, it was evident that a clear proportion of the students did not have a coherent view of the genetic relationship between cells (Lewis et al., 2000b). This makes sense as to why students were confused between mitosis and meiosis. They did not understand the Theory of Cell. The majority of students made no distinction between somatic and sperm cells. The most common view was that genetic information within a cell is determined by the structure, function, or even position of that cell. A more innate study by Saka et al. (2006) to investigate the location of Gene, DNA and chromosomes indicated that students thought that genes were a different structure from DNA. Their drawings also supported their explanation. Figure 2.1 shows a drawing by students to reveal the location of gene, DNA and chromosomes.

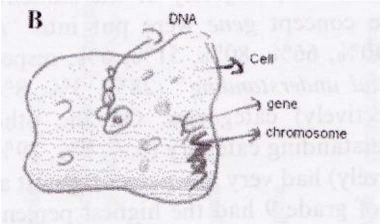


Figure 2.1. A drawing by a student

Outcomes of the study conducted by Riemeier and Gropengieβer (2008) indicated some major difficulties in learning cell division:

i. Students' understanding of growth as becoming mature. The students did not think about the levels of cells to explain the growth of onion roots.
ii. Students' understanding of cell division as multiplication of cells. Growth meant increasing the number of cells.
iii. At the level of the nucleus, they imagined the division of the nucleus, but without thinking about previous breakdown of the nuclear envelope.

iv. Students' understanding of cell division as a decrease in the number of chromosomes and an enlargement of the nucleus.

A re-visiting research conducted on students' understanding of genetics and cell revealed, more than three quarter of the students stated that genes were important determinants of characteristics (Lewis & Kattmann, 2004). However, students did not appear to grasp any coherent understanding of the biological mechanism by which this may be achieved. There was no recognition of the gene as a physical entity with a specific location and no clear understanding of the relationship between genes, chromosomes and DNA. No clear distinction was made between 'gene' and 'genetic information' either. These findings suggest that students have a very poor understanding of the purposes, processes, and products of cell division and made little distinction between mitosis and meiosis. Some difficulties encountered for these concepts include:

i. A general uncertainty about the nature and role of chromosomes.
ii. Confusion about the relationship between chromosomes and genes.
iii. A failure to recognise that a gene has a specific physical location on a chromosome.

Given this uncertainty and confusion about genes and chromosomes it is difficult to see how these students could recognise the implication of cell division – that as chromosomes replicate, genes replicate; and when the new cell receives a copy of the chromosomes it also receives a copy of each gene on these chromosomes; as a result, each new somatic cell must contain the same genetic information as the parent cell. Without understanding the process that takes place in the cell, it would prove difficult for students to develop a coherent explanation on the whole.

Ozcan, Yildirim and Ozgur (2012) in their research found that students knew DNA duplicates during Interphase as knowledge, but they did not know what exactly happened in the cells. Students were also unable to answer how these cells had the same chromosome potential at the end of the mitosis. Students also encountered difficulties in explaining chromosome, DNA and gene concept as well as recognising the relationship among the concepts. Concepts such as chromosomal structure of the cells after mitotic and meiosis divisions, diploid and haploid cell concept, cell number after mitotic and meiosis division, homologous chromosome, structure of chromosomes and incidents happening during the mitotic and meiotic division were some of the hardest to be grasped by the students.

Mechanistic Reasoning

Literature reviews show that students have failed to acquire a coherent conceptual understanding which in relation to the Theory of Cell. This is due to a lack of consistency between the levels of biological organisation. The concepts often remain fragmentary because they are mainly drawn from a subcellular level and not sufficiently integrated with concepts at a cellular and organism level (Verhoeff et al., 2008). Mak et al. (1999) pointed that students may have learned biological processes such as photosynthesis in isolation according to the syllabus layout. This compartmentalisation of concepts, which are also common in other areas of biology learning, prevents the students from developing a coherent understanding. Lazarowitz and Lieb (2006) stated that the difficulties in learning biology can be attributed to two reasons: the appropriateness of the biological organisation level and the level of conceptual abstraction. When students were asked to relate simultaneously to more than one variable in one test or when required to use their relevant knowledge in reasonable answers, they encountered difficulties. Concepts such as photosynthesis, respiration, enzyme activity, and genetics especially require formal reasoning which students lack of. According to Johnson and Lawson (1998), two factors may influence students’ success in learning biology: mainly, students’ prior knowledge and their reasoning ability. Even though students have sufficient declarative knowledge of the cell, they are still lacking coherence when dealing with biological processes. This was corroborated by a study conducted by Abrams et al. (2001). Students were able to list out the components involved in a certain process; however, they could not give an explanation for the process. For example, when students were asked to describe the process of photosynthesis, many of them explicated that photosynthesis involved carbon dioxide, light and energy while ATP and glucose were the products of photosynthesis. The lack of coherence in the components involved in photosynthesis restricted the students from giving process explanation and most of the biological processes begin in the organelles of the cell. Lawson and Thompson (1988) noted that students who had acquired higher order reasoning held fewer alternative conceptions as reasoning patterns could overcome misconception. Numerous studies have revealed the importance of mechanistic reasoning (Darden & Craver, 2002; Darden, 2002; Gopnik et al., 2001; Jonassen & Ionas, 2008; Russ et al., 2008; Southerland et al., 2001; Thagard, 1998). The following section will focus on the categories of reasoning, the definition of mechanistic reasoning, its importance and its characteristics.

Definition of Mechanistic Reasoning

What is mechanistic reasoning? Before exploring and looking at mechanistic reasoning, we have to understand what mechanisms are and how reasoning about mechanisms affect the inference of causes from correlations. A mechanism is a system of parts that operate or interact like those of a machine in order to make them move. Table 2.1 displays some of the most important mechanisms. Different sciences employ different kinds of mechanisms in their explanation (Thagard, 1998).

Table 2.1

List of Some Important Mechanisms in Science (Thagard, 1998)

Science	**Parts**	**Changes**	**Interaction**
Physics	Objects such as sun and planets	Motion	Forces such as gravitation
Chemistry	Elements, molecules	Mass, energy	Reaction
Evolutionary biology	Organisms	New species	Natural selection
Genetics	Genes	Genetic transmission and alteration	Hereditary, mutation, recombination
Geology	Geological formation such as mountains	Creation and elimination of formations	Volcanic eruptions, erosion, etc.
Plate tectonics	Continents	Motion such as continental shift	Floating collision
Neuroscience	Neurons	Activation, synaptic connections	Electrochemical transmissions
Cell biology	Cell	Growth	Cell division
Cognitive science	Mental representation	Creation and alteration of representations	Computational procedures

Jonassen and Ionas (2008) stated that mechanisms are conceptual descriptions of causal relationship. They specifically answer the “why” questions as well as the “how” questions. Thagard (2000) commented that mechanisms represent qualitative understanding because they explain how and why the cause(s) produce the effect. Mechanistic reasoning attempts to explain the mechanisms that take place between cause and effect. Without conceptually explaining the underlying mechanisms of a causal relationship, the learner will not be able to build a coherent conceptual model of domain content, which will preclude problem-solving and other higher-order activities with a domain (Jonassen & Ionas, 2008). Thus, to understand and answer biological processes, learners must describe the mechanistic attributes to the relationship. According to Russ et al. (2008), mechanisms are non-teleological, causal, reductive and built from phenomenological evidence.

i. Non-teleological

Teleological is an explanation in which the ends are considered the agent in determining the nature of the phenomena. (Clough & Wood-Robinson, 1985).For example, plants need sunlight, so they grow towards the sun. However, in describing mechanistic reasoning, Abrams et al. (2001) contrasted students' mechanistic reasoning as those who describe "the how" for the change rather than "the why (the rationale)" for change. In tracking students' construction of explanation, Metz (1991), similarly, found that no teleological thinking is manifested in giving explanation. Russ et al. (2008) distinguishes mechanistic reasoning and teleological in scaffolding students' explanation. Hence, mechanistic reasoning is non-teleological.

ii. Causal

Tabery (2004) mentioned that causal explanation often consists of mechanisms. Russ et al. (2008), likewise, corroborated that adequate identification and underlying mechanisms in explanation for natural phenomena is required in many scientific fields of research. For example, Thagard's (1998) work on correlations, causes and mechanisms highlighted that the understanding of mechanisms in the causal network is essential in giving medical explanation. In fact, most of the medical researchers are highly concerned with finding mechanisms that explain the cause of diseases and through understanding the mechanisms, researchers could discover the treatment of those diseases. Abrams et al.(2001), Carey (1995), Janssen and de Hullu (2008), Metz (1991) and Schauble (1996) argued that a causal mechanism is the process of how a change brings about an effect.

iii. Reductive

Causality sometimes engages a broad perspective in giving an explanation Thus, some researchers focus on the reductive nature of mechanistic explanation (Russ et al., 2008). Russ et al. (2008) adopted Chin and Brown’s (2000) mechanistic thinking with a deep approach to science which states that microscopic explanation gives rise to cause and effect explanation. Micro and macro levels are fundamental in reasoning. Carey (1995) also claimed that causal mechanisms rely on the entities that interact with each other. Russ et al. (2008), again, emphasized that researcher commonly used reductionist models to describe the structure of the phenomena. In biology, scientists often deal with the micro level of explanation beginning with the Theory of Cell to the macro level which is the system. Therefore, mechanisms account for showing the underlying object that causes change which is related to each other from the macro to the micro level.

iv. Built from phenomenological evidence

Russ et al. (2008) adapted diSessa’s (1993) “phenomenological primitive” (p-prims) where mechanisms are built. Using this perspective, students’ explanations are extracted from common everyday experiences to describe a novel situation. Thus, the learner may construct a number of explanations based on the response to a single phenomenon, and learner experience (p-prims). Hence, during mechanistic reasoning, students use p-prims to access the likelihood of events, explain what will happen given the past or what can happen by giving current states and predict the circumstances in the future (diSessa, 1993). Piaget (1927) and Ausubel (1968) asserted that prior learning components or experiences evoke students’ learning by familiarising or assimilating previous knowledge into existing knowledge.

Mechanistic Reasoning in Biology

The discovery of different entities and activities are important aspects in scientific practice. In fact, much of history in science gives mechanistic reasoning when tracing the uncovering of new entities and activities. Machamer et al. (2000) stated that the modern idea of mechanistic reasoning became current in the seventeenth century when Galileo articulated a geometrico-mechanical form of explanation based on Archimedes's simple machines and soon expanded to become widespread across Europe. It was known as "mechanical philosophy" at that time. In the eighteenth and nineteenth centuries, chemists and electricians began to look for other entities and activities (mechanistic reasoning involves entity and activity) for further explanation in one concept which acts as a fundamental aspect in discovering the structure of the world. The nineteenth century also saw an emerging emphasis on the concept of energy and electromagnetism (Machamer et al., 2000, p. 15). From time to time, scientists give fresh mechanistic reasonings in order to explain better how our world works. At different periods of time, in different fields, different mechanisms, entities and activities have been discovered and accepted. Hence, preparing students to think like scientists using mechanistic reasoning will equip them in future scientific fields. One example of such a discovery in biological processes using mechanistic reasoning is discussed here. This is protein synthesis (adopted in Craver & Darden, 2002).

Discovery of Protein Synthesis

Protein synthesis engages complicated mechanistic reasoning. The unfolding of mechanisms of protein synthesis by scientists has brought a huge leap in the world of Biology and Chemistry. This is because both molecular biologists and biochemists have brought forth different mechanistic reasoning of how proteins are synthesised. The results are eventually integrated to produce a description for protein synthesis. The discovery of protein synthesis revealed the gene expression in molecular biology and the synthesis of enzyme and structural protein that are important in the study of metabolism in chemistry.

By the 1940s, biochemists had discovered over twenty amino acids and the nature of connection between them in peptide bonds. Paul Zamecnik, a biochemist, and his colleagues tried to understand energetic intermediates between free amino acids and their linkage in polypeptides. Thus, they reasoned forward by focusing on chemical reaction and energy requirements in searching the relationship from peptide bonds to polypeptide. On the other hand, molecular biologists, James Watson and Francis Crick had initiated the discovery of DNA. They sought to understand the ‘genetic code’ which are the bases of DNA. Hence, they were reasoning forward from DNA to amino acids sequence in proteins. Both biochemists and molecular biologists used different technique to explore how protein was synthesised.

By homogenizing and tracing centrifuge rat liver, Zamecnik later discovered the functional unit in a microsome which is the location of protein synthesis (later known as ribosome). Biochemists and cytological studies have shown that RNA was part of the microsome and might be related to protein synthesis. However, the function of RNA remained vague in 1954. In contrary, Watson and Crick hypothesised that RNA might determine the activity of amino acids. Watson’s idea was that RNA was copied based on DNA to form a structure with different holes which would be fitted with different amino acids. It filled the gap between DNA and protein. Figure 2.2 shows the discovery of protein synthesis by Zamecnik and Watson and Crick.

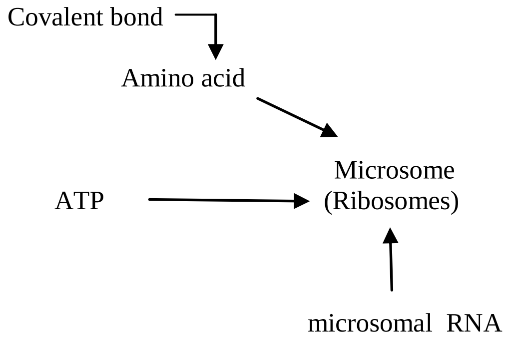
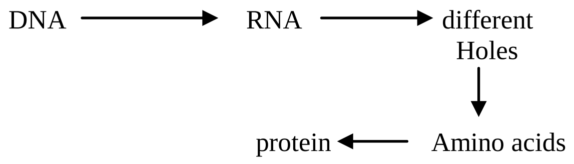
Zamecnik's mechanistic reasoning for protein synthesis	**Watson's mechanistic reasoning for protein synthesis**
Backward reasoning	Forward reasoning
	

Figure 2.2. Discovery of protein synthesis by Zamecnik and Watson and Crick

While Watson and Rich have unsuccessful in searching the RNA structure using the X-ray technique, Zamecnik and colleagues focused on the intermediate steps which occurred between free amino acids and the formation of peptide bonds. They found the high energy and enzymes were required to free amino acids. They also discovered a bit of soluble RNA which is different from microsomal RNA. However, this soluble RNA was covalently bound to amino acids (this was later known as transfer RNA). In 1956, after Watson visited Hoagland in Zamecnik's lab, scientists integrated both mechanistic reasoning from biochemical and molecular fields to contribute to the process of protein synthesis.

The anomalies that arose in the late 1950s lead to the discovery of messenger RNA. DNA has transcribed into messenger RNA and it thus carried the genetic code for amino acids during protein synthesis. In searching for the productive continuity of protein synthesis, scientists often gave mechanistic reasoning by forward chaining and backtracking to relate the entities and activities that have involved in the process from different fields. The case revealed the importance and strategies of mechanistic reasoning when scientists tried to solve the unknown. The strategies of mechanistic reasoning will be further discussed.

Strategies of Mechanistic Reasoning

Ploger (1991) claimed that mechanistic reasoning involves mechanisms that assist students in cognitive change. For example,

Level of Description	**Term/ Relation**
Biological structure	Glucose Insulin Muscle
Input-output relationship	Glucose enter the muscle As long as insulin is present
Mechanism	Insulin interacts with a specific cell receptor Permitting glucose uptake by muscle cells

A very brief explanation given by Ploger (1991) on what the characteristics and strategies of mechanistic reasoning are still remains ambiguous. Thagard (1998) explained that a mechanism is a system of parts that operate or interact like machines, transmitting forces, motion and energy to one another (p. 66). Thagard (1998) claimed that mechanisms consist of parts that operate together and the interaction is fundamental during the process. There are three strategies to form mechanistic reasoning. Firstly, explanation is not deductive. Deductive explanation might be useful in other fields such as physics or mathematical laws. However, in biological processes, it is far too complex to generalise deductive explanation. For example, we cannot deduce that smoking will cause lung cancers. In fact, non-smokers might get lung cancers as well and smoking might cause other types of cancer. Secondly, explanation is not statistical. Statistics might show the cause and effect of certain circumstances. However, there is availability of other mechanisms that contributes to the circumstances. Thirdly, an explanation is not in terms of single causes. As explained above, explanation is not deductive, and does not occur due to single causes. Diabetes, for example, is now rising from complex factors such as hereditary, obesity, glucose consumption and inactivity. This is possibly because of protein that reduces glucose intake. Thus, mechanistic reasoning does not explain or assume that it is from single cause.

However, this does not clearly show the strategies of mechanistic reasoning and mechanistic reasoning is far more than a reasoning that brings cause and effects. Jonassen and Ionas (2008) stated that a mechanistic explanation is an explanation that describes the process when targeted could have produced an effect. He believed that mechanistic reasoning includes a notion of force or necessity, a process that takes place between two entities and the nature about the mechanisms. He emphasised the use of entities and the nature in constructing mechanistic reasoning.

Machamer et al. (2000) claimed that mechanisms are entities and activities organised such that they are productive of regular changes from start or set-up to finish or termination conditions (pg. 3). Craver (2001) and Darden and Craver (2002), similarly, declared that mechanisms are components that work together to do something. It consists of entities and activities that are organised in productive continuity from beginning to end (pg. 4). For example, types of entities include ions, macromolecules (such as protein, nucleic acids, DNA and RNA) and cellular structures. Types of activities include lock and key mechanisms of an enzyme and substrate and electrochemical activities. Both entities and activities are interdependent.

Craver (2001) adopted Cummin's (1975) explanations to yield more detail in mechanistic explanation. Cummins uses $\{S\}$, $\{X_{1,}\ X_2\ldots\}$, $\{\phi_1, \phi_2\ldots\}$ and $\{\psi\}$ to elucidate the linking of components in the circulatory system. However, Cummins does not explicate the relation between S and X (Craver, 2001, pg. 55). The functional statement in Cummins is as follows, which is known as "regimented reconstruction":

> *X functions as a ϕ in S(or the function of in S is to ϕ) relative to an analytical account A of S's capacity to ψ just in case X is capable of ϕ-ing in S and A appropriately and adequately account for S's capacity to ψ by, in part, appealing to the capacity of X to ϕ in S.* (1975, pg. 190)

For example, the heart (X) has the function to pump blood (ϕ) in the circulatory system (S) relative to an analytical account (A) of the circulatory system's (S's) capacity to deliver oxygen and calories to body tissue (ψ) just in case the heart (X) is capable of pumping blood (ϕ-ing) in circulatory system (S), and analytical account (A) appropriately and adequately accounts for the ability of the circulatory system (S) to deliver oxygen and calories to body tissues (ψ) in part by appeal to the capacity of the heart (X) to pump blood (ϕ) within the circulatory system (S) (Craver, 2001, pg. 55). Cummins' regimented reconstruction distinctively pointed out the relationship between the components involved in a system. The entities in mechanistic reasoning corresponded with Cummins' $\{X_{1,} X_2\ldots\}$; such as hearts, kidneys, and veins. The activities in mechanistic reasoning can be represented as $\{\phi_1, \phi_2\ldots\}$ in Cummins' account. Therefore, mechanisms can be described as how entities (Xs) and activities (ϕs) are organised to do something (ψ).

Craver (2001) exclaimed that entities and activities are inter-reliant and suggested they are spatial and temporal to organise to yield active mechanisms in reasoning. Spatial organisation of mechanisms enables us to speculate the properties of entities for example the size, shape, orientation and location *in situ* that allow them to engage in certain activities. For example, the right ventricle in our heart has a thicker wall compared to the left ventricle since the right ventricle is required to pump blood to all parts of the body. Understanding the orientation and organisation of this mechanism, students could foresee the action. The order, rate and duration for activities are crucial in a process. For example, deoxygenated blood entering the heart via the vena cava is then pumped through the pulmonary artery to the capillary of the lungs. The sequence of the blood flow is impossible to change. Therefore, learning mechanisms provide important information on how it works or how it does not work.

Darden and Craver (2002) further proposed incorporation of forward and backward chaining in spatial and temporal organisation of mechanistic reasoning. By looking forward, each stage must give rise to allow, drive or move to the next step. Conversely, looking back, each stage must have been produced, driven or allowed by previous stages(s) (Darden and Craver, 2002, pg. 4). In searching for productive continuity of the mechanism, one must find an activity for each entity and an entity for each activity (pg. 19). Another character for constructing mechanistic reasoning is scheme initiation. Schemata is like a black box which has varies degrees of abstraction. These schemata can be filled with activities or entities as they are discovered. For example, in explaining protein synthesis, students might answer protein is synthesis in ribosome. However, how ribosome initiates the protein synthesis process could act as a schemata initiation for the students to seek for more information.

Darden and Craver (2002) suggested that each entity and activity is able to contribute to forward chaining and backtracking. Entities in forward chaining, or known as activity enabling properties entities, allows one to speculate the properties of entities and engage in respective activities. On the contrary, activity in forward chaining allows one to conjecture the properties of entities in the subsequent stage. This is known as activity consequence. In backtracking, the properties of entities can provide clues to the activity produced. If more than one entities' property is involved, providing a hint on a previous activity occurrence, this is known as activity signature. Alternatively, entities signature refers to properties of activities which provide clues to prior entities that lead to those activities. Further explanations are as follows:

i. Activity-enabling properties of entities

During forward chaining, one could speculate the kinds of activity that given entities are engaged in. Such properties may include three-dimensional structures and size, orientation and location. For example, a structure may promote or inhibit activity; three dimensional shapes can open or close activity. An entity may involve more than one property. For instance, charges and three dimensional shapes of the active site influence the enzymatic activity. Therefore, discovering the structural properties of an entity often give clues to the kinds of activities in next stage.

ii. Activity consequences

Activities have properties such as rate, duration and, strength of influence (pg. 23). One may ask by giving prior occurrences of some activity, how one can predict the expected entities in the subsequent stage? In an enzymatic reaction, for example, when substrates bind with the active site of an enzyme (activity), the shape of the active site might possibly change or the charges at the active site can neutralise (entities) thus permitting the following activities to occur. Knowledge of these entity-enabling properties of activities allow us to reason forward about the related mechanisms in the next stage.

iii. Activity signature of entities

In backtracking, one may use properties of entities to explain prior activities. Thus, one may ask how such entities give rise to or allowed the occurrence of the activity? By decomposing the end products, it may reveal their ingredients and thus provide what activities could be involved. In protein synthesis, for instance, biochemists decomposed proteins into amino acids (entities) and upon further investigation showed amino acids are joined by covalent peptide bonds. How peptide bonds are formed (activity) is a necessary preceding step to backtrack the protein synthesis process. This occupies activity signatures that aid backtracking.

iv. Entity signatures of activities

The features of an activity may provide hints to the entities that we are engaged in. Distinct kinds of activities require distinct kinds of entities with distinct kinds of properties to produce them (pg. 24). For example, in an enzymatic reaction (activity), the substrate and the active site of the enzyme must have a complementary structure (entity) in order to fit in. One might also find the charge might influence the enzymatic reaction.

Machamer et al. (2000) further explained that there are 3 steps in constructing mechanism: set-up conditions, intermediate condition and termination condition. In set-up condition, mechanisms begin with describing the set-up condition. These conditions maybe the result of prior processes. The start conditions include relevant entities and their properties. Structural properties and orientations are often crucial for showing how entities will be able to carry the activities to the next stage. For example, in enzyme synthesis, students would have to recognise the properties of enzymes before explaining the synthesising process. An enzyme is a type of protein which acts as a set-up condition in this case. Intermediate activities describe the relevant entities, properties and activities that link together to produce an action at one stage which affects another stage. Termination condition describes the end of the mechanisms. This condition might be a state where the entities are at rest, equilibrium, neutralisation of charge or production of a product.

Russ et al.(2008) put forward a more explicit study on mechanistic reasoning and seven strategies were identified namely (1) Describing the Target Phenomenon; Identifying (2) Set-Up Conditions, (3) Entities, (4) Activities; (5) Properties of Entities, (6) Organisation of Entities; (7) Chaining; Analogies; and Animated Models.

i. Describing the target phenomenon

A phenomenon might initiate the discovery of mechanisms involved, or predict phenomena based on their prior knowledge of relevant components.

ii. Identifying set up condition

Set-up conditions are descriptions of the spatial and temporal organizations of components that begin the regular changes of the mechanism that produce the phenomenon (p. 79).

iii. Identifying entities

One of the fundamental components in mechanistic reasoning is identifying the entities engaged in a certain activity. Entities are components or things that lead to the occurrence of certain phenomena.

iv. Identifying activities

Once students identify the entities, relevant activities of the entities will emerge. The changes of the entities describe the activities involved.

v. Identifying properties of entity

An entity must consist of certain properties to promote an activity.

vi. Identifying organisation of entities

Mechanisms mostly depend on how entities are spatially organised, for example, where they are located, and how they are structured. The organisation of entities might guide us to identify the properties of an entity or the activity.

vii. Chaining

As emphasised by Darden and Craver (2002), chaining forward and backward is essential in producing a high level of mechanistic reasoning. Chaining forward and backward allow us to backtrack on what happened previously that could lead to the current situation or by giving certain entities and activities, we can predict the next stage of activities or entities.

Sometimes students need external cognitive representations to figure out the mechanistic reasoning. Thus, analogy and animated models are often utilised.

Many areas of science have developed by discovering mechanisms and generating mechanistic reasoning towards certain phenomena. Figure 2.4 shows the evolution of the meaning and strategies of mechanistic reasoning discussed in the literature review. The value and importance of mechanistic reasoning will be discussed in the following section.

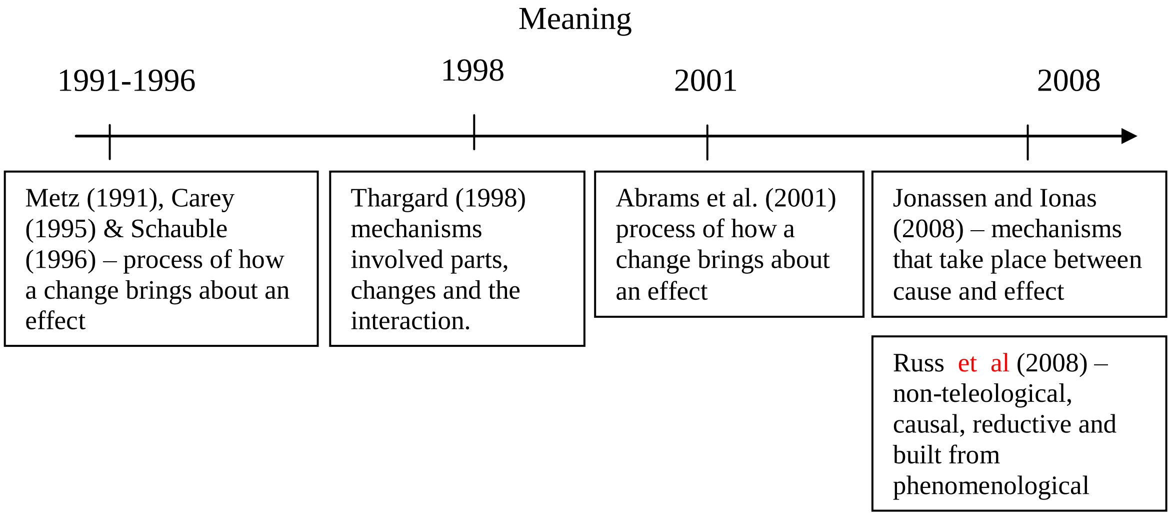


Figure 2.3. Evolution of the meaning and strategies in mechanistic reasoning

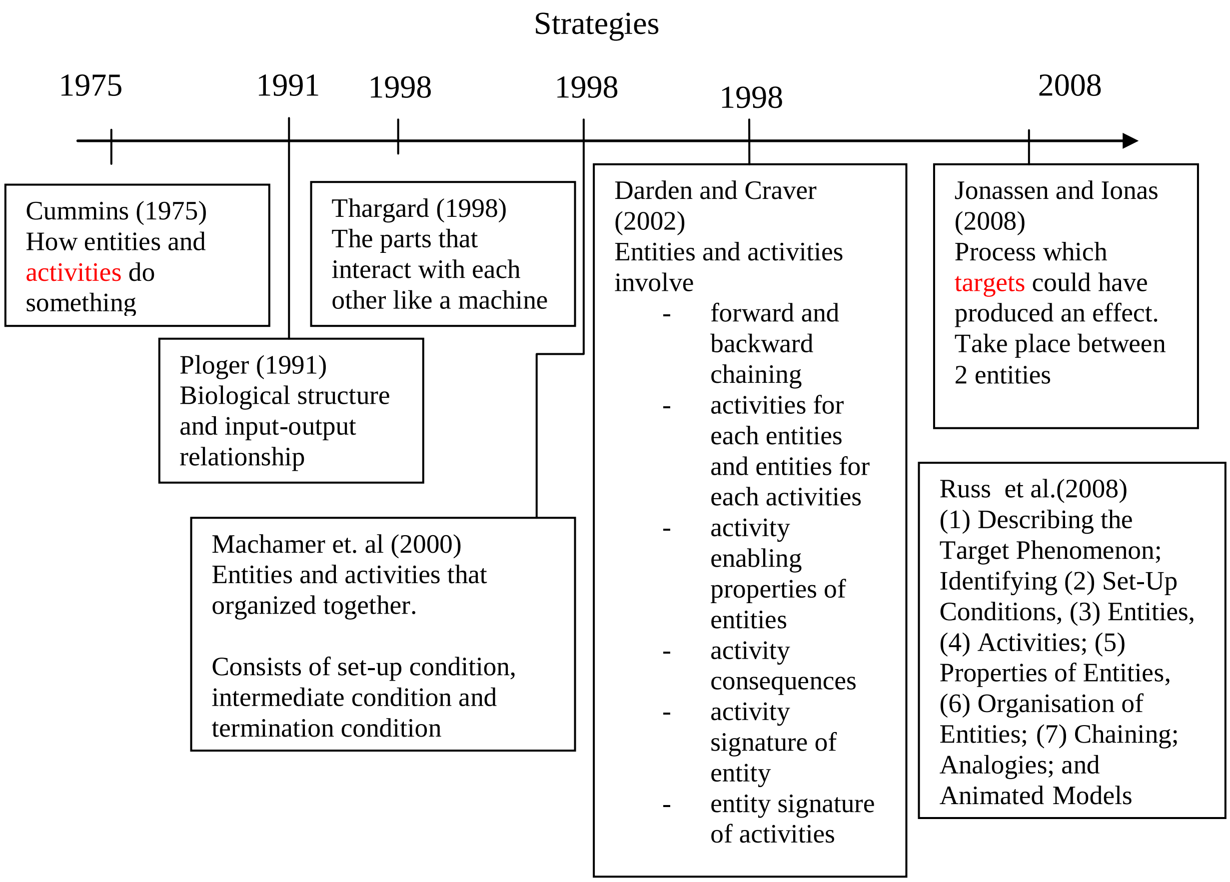


Figure 2.3. (*Continued*)

The Value of Mechanistic Reasoning

Long time ago, scientists used mechanisms to discover the role or functions of certain processes. A manifest example was given by Darden and Craver (2001) on how the mechanism of protein synthesis was discovered by biochemists and molecular biologists in the 1950s and 1960.

Initially, the approaches to ascertain the protein synthesis process were very different. Different scientists focused on different components and mechanisms from different methods. By about 1965, the results from the scientists were integrated. Studies on scientific works reveal general strategies for discovering mechanisms.

Mechanisms provide different ways of thinking about discovery, integration and reasoning to bring about change in the scientific world. Discovering and thinking about the mechanisms bring a new perspective on interfiled relationship. As in learning, students should be taught how scientists think and discover instead of being spoon fed them with facts to answer exam questions.

Mechanistic reasoning is crucial in searching for new paradigms, extending the process of construction and unfolding the relationship in certain components (Darden & Craver, 2001). In biology, most scientists explain phenomena through investigating the mechanisms involved. As Machamer et al. (2000) said, mechanism descriptions show how possibly, how plausibly, or how actually things work. The intelligibility in science does not focus on the explanation's correctness but the relation between entities and activities, set-up conditions and termination condition. For example, Glennan (2002) stated that a mechanistic reasoning of Mendel's law of segregation will describe the meiotic mechanism that produces gametes and shows how this mechanism creates an equal number of gametes containing each allele of a give locus.

Machamer et al. (2000) concluded that thinking about mechanisms gives a better way to think about the interaction. Thinking about mechanisms offer an interesting and good way to look at the history of science. Thinking about mechanisms also provides a descriptively adequate way of talking about science and scientific discovery. Thinking about mechanisms presages new ways to handle some important concept and problems. In fact, if one does not think about mechanisms, one cannot understand the world of biology (pg 23 and 24). Machamer et al. (2000) stated the significant use of mechanistic reasoning not only helps one in the present moment, but also for future discoveries.

Thagard (1998) claimed that medical researchers are highly concerned with finding mechanisms that explain the occurrence of diseases and for therapeutics purposes. Understanding the mechanism that produces a disease can lead to new ideas about how the disease can be treated. Thagard (1998) in his study pointed out the importance of mechanistic reasoning in explaining the cause and effect in duodenal ulcer production by associating different concepts (refer to Figure 2.5).

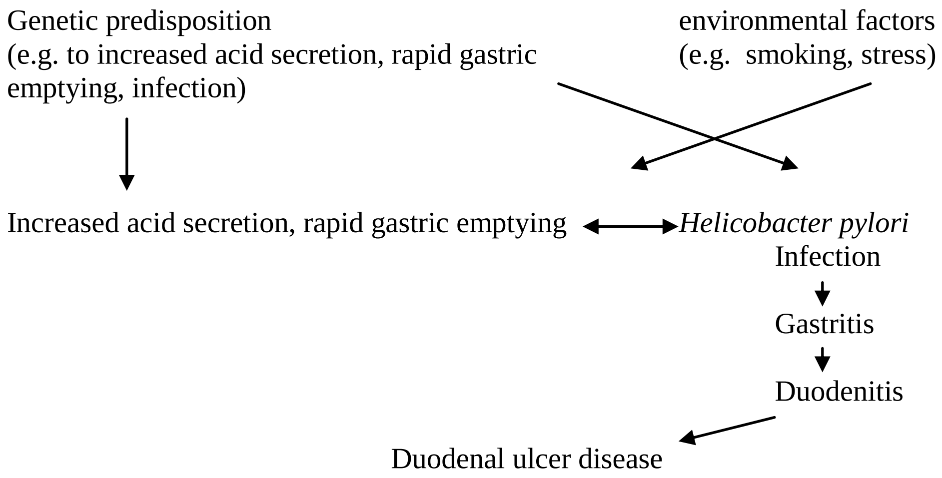


Figure 2.4. Mechanisms of duodenal ulcer disease

Thagard (1998) also mentioned the searching of the mechanisms for cancer that has been ongoing since the 1970’s and 1980’s up till the present. They discovered that cancer is the result of uncontrolled cell growth arising from a series of gene mutations. His example is similar to how scientists discover the process of protein synthesis.

Russ et al. (2008) believed that mechanistic reasoning is more effective than formal empirical investigation. It would take too much time to perform all possible variables in possible control experiments. Even though many of the students could carry out controlled experiments stated in the text book, they could not solve all the science problems. This was because it is known that scientists often utilise mechanistic reasoning to narrow down the possible variables for further testing. Secondly, mechanistic reasoning is more likely to yield accurate conclusions than formal empirical investigations. Students could produce more accurate observations for cause and effect for certain situations if a mechanism is known to underlie an existing covariation. Knowledge of mechanisms makes us more certain of which covariation indicates causality. Therefore, students should be encouraged to draw conclusions from mechanistic reasoning. Thirdly, mechanistic reasoning is helpful in solving a novel situation. Students should not only be taught how to solve problems within the textbook; they should be able to make sense of novel situation. It is unlikely that students have stored covariation information when faced with physical situations even though they have enough knowledge. Knowing the entities, activities and using forward and backward chaining in mechanistic reasoning could assist them to understand the problems and look for solutions.

Comparison with Other Types of Reasoning

Biological reasoning is generally divided into two complementary types which are analytical and synthetic reasoning (Cooke, 2008). In Biology, mechanistic reasoning is more accurately described as an analytical process. Mechanistic reasoning involves breaking up a complex biological system into its component parts, analysing their isolated activities and group interactions, and most importantly constructing a plausible mechanism involving the parts and their interactions. “Evolutionary reasoning” involves the reasoning about evolutionary questions, but comparable reasoning attempts to deal with other processes such as historical constraints, developmental canalizations, emergent phenomena, and design features, e.g., scaling and fractal geometry (Cooke, 2008). This type of reasoning is sometimes known as holistic reasoning. It is best described as synthetic reasoning. Table 2.2 shows the comparison between mechanistic reasoning and evolutionary reasoning.

Table 2.2

Comparison between Mechanistic Reasoning and Evolutionary Reasoning (Cooke, 2008)

Conventional term	Complementary term	Description
Analytical reasoning	Synthetic reasoning	Emphasizes the reasoning process
Mechanistic reasoning	Evolutionary/ cosmological reasoning	Mechanistic reasoning encompasses two different processes
How questions	Why questions	Useful vernacular terms, but obscures the commonality of evolve/cosmo reasoning and synthetic reasoning
Scientific method	n/a	Implies that only analytical reasoning is considered as being scientific
Reductionism	Holism	Have philosophical baggage; may even have pejorative connotations
Experimental	Theoretical	Clear to physicists, but have different meanings for biologists

Tabery (2004) mentioned that causal explanation often consists of mechanisms. Hoerl (2011) explained that causal reasoning turns on the idea of a physical connection between cause and effect. Hoffman, Klein and Miller (2011) stated that causal reasoning drives decision making. It is the central to understand events and modify their causal model based on what they have learnt. Causal reasoning also plays a central role in our mental model on how things work and what will happen. Thus, the researcher can argue that mechanistic reasoning is part of causal reasoning; nonetheless, mechanistic reasoning focuses more on the components or mechanisms that work together in order to explain the cause and effect about certain scientific phenomena.

High and Low Achievers

Mechanistic reasoning involves high-order mental processes in learning. However, many individuals lack these abilities. Countinho et al. (2005) stated the implications of higher order thinking that will lead to good academic performance. Learners with higher order thinking realise what they do not know and take steps to remedy the problem. On the contrary, low performers' lack of logical reasoning ability might lead to poor academic performance. Besides, Countinho et al. (2005) further elaborated that high performance students are high in need for cognition which generates more complex and elaborate explanations of target concepts and have better grades on tests than students low in need for cognition. Thomas and MacGregor (2005) compared solving problems among high and low achieving students and found out that high performing students identified their problems during the planning stage, whereas the lower performing group started the planning during the planning stage and was still doing so during the development stage. High performing groups make apparent progress, such as clarifying the goal, exploring and acting on strategies once they have identified the problem. The low performing group still continue to explore strategies even though they have proceeded to the development stage. Thomas and MacGregor (2005) also found out that low performing students accepted task-related suggestions without questions whereas high performing students have more in depth discussions and provoke questions for exchanging ideas.

A study by Simons and Klein (2007) also indicated that higher achieving students score better in problem-solving questions than lower achieving students because low-achieving students find it hard to search for information that would lead to obtaining content knowledge. Cook et al. (2008) explained that novice learners (refers to low-achievement students) have knowledge that is not heavily interrelated and not hierarchically organised into a framework to make sense of new information. Therefore, they have difficulties in looking for appropriate information to link them together. This was mentioned, likewise, by diSessa (1993) that novices have knowledge stored in small chunks and are only weakly connected. On the other hand, experts (refers to high-achievement students) have cognitive schemas that are previously constructed and can be easily retrieved. They have better links between their mental representations to related principles of content. Hence, these learners are able to choose appropriate schema to help understand new information. Cook et al. (2008) also elucidated that novices often experience problems in identifying conceptually relevant features. They generally focus on surface features to make links. However, experts have larger chunks of information built up hierarchically in an organised framework.

Meanwhile, research by Zohar et al. (2001) and Zohar and Peled (2008) stated that most of the teachers interviewed believed that higher order thinking is an important educational goal; however, it is inappropriate for low-achieving students as the cognitive demands of tasks requiring higher order thinking were beyond the capabilities of low-achieving students. In addition, educators see these students as “stuck” in the early phase of learning compared to high-achieving students who have mastered the basic skills and more prepared to handle more complex learning tasks. But Zohar et al. (2001) claimed that thinking is applied to all learning and to all learners (p. 470). In fact, he argued that lower-achieving students benefit most from instruction of higher order thinking. Studies investigating different higher order thinking activities given to high and low achieving students are influenced by how teachers judge higher order thinking skills activities to be ineffective for low achieving students, whom are purportedly seen as ill prepared to handle higher order thinking activities and in need of a remedial regimen of achieving students (Torff, 2006; Warburton & Torff, 2005; Zohar, Degani & Vaakin, 2001; Zohar & Dori, 2003). According to this line of reasoning, this may result in which low achieving students receive less high order thinking activities, which restricts their academic growth, which in turn makes high order thinking activities less likely to be used; in contrast, high achieving students might receive abundant high order thinking activities since they are believed to be able to handle the activities, which enhance their academic growth and make more high order thinking activities instruction to be likely to be carried out. Similarly, Yu, She and Lee (2010) have indicated that low achieving students higher order thinking skills (HOTS) such as mechanistic reasoning might not be reflected in their academic achievement. The statistical results in her research showed that low academic achievers performed better than the high academic achievers in a non-traditional test form and the authors believed that the findings indicated that the infusion of higher order thinking skills (HOTS) among low achievers is possible.

Methodological Aspects in Mechanistic Reasoning

Pearsall, Skipper and Mintzes (1997) in their research stated that successive and progressive changes in the structural complexity of knowledge can be done by using concept mapping throughout a long period of time. In their studies, they had assembled a set of four maps for every student for one semester. Each map can represent a kind of fleeting picture of students' understanding and, it provides a glimpse of the dynamic process of knowledge construction when viewed in series. von Aufschnaiter and von Aufschnaiter (2003) in investigating students' cognitive processes utilising 51 activity cards with 85 tasks. They stated that it is important for students to work on tasks or receive instruction from a plan environment. During analysis, Thomas (2003) showed that the first step in analysing the qualitative data is preparation of raw data (which is also known as "data cleaning"). In this preparation of raw data, Thomas (2003) used the example by McGregor (2003) in explaining how the text units were being merged before categorisation began. Similarly, Gibbs (2007) also stated that in social research, merging collection and analysis from different sources is the first step in analysing qualitative data. In the context of the present research, merging of data was also employed.

As for mechanistic reasoning, Ploger (1991) carried out a study on reasoning in biology using story generation, historical information and a computer modelling method. In this story generation, students were asked to tell a story about how the body works, using a set of terms. Seeking mechanistic reasoning from historical information involves reconstructing some aspects of the research that leads to importance of discoveries in biology. Ultimately, computer modelling requires construction of computer models of intake of glucose by muscle cell based on reasoning from historical information.

Abrams et al. (2001) studied mechanistic reasoning using observation and interviews involving students from different regions and a second, fifth, eighth and twelfth grade classroom were chosen from each locality. The classroom context was observed for one week before the interviews were carried out. During the interview, the students were presented a series of graphics depicting natural phenomena. After observing, students were asked a series of questions. All interviews were audiotaped and videotaped. The audiotaped was a primary source of transcription, with additional comments such as student’s actions or gestures from videotapes. Field notes were taken into account as one of the data sources.

Between the years 2000 and 2002, papers related to using mechanism in explanation (refers as mechanistic reasoning) have created attention on the importance of mechanistic reasoning. Thagard (1998) wrote a paper on how mechanisms contributed to explaining diseases and interrelated several factors. Machamer et al. (2000) explained how giving mechanisms explanation worked in neurobiology and molecular biology. Thinking in terms of mechanisms provides a new inspection of causality, laws, explanation, reduction and scientific change (Machamer et al., 2000). Craver (2001) further explained the function of mechanism in explanation using Cummin’s account. Darden and Craver (2002) discovered the strategies in the interfield discovery of the reasoning which is schema instantiation and forward chaining/ backtracking. Darden and Craver (2002) commented that attention to mechanisms is a salient feature in providing general reasoning strategies. The reasoning strategies discovery by Darden and Craver (2002) is further elucidated in Darden's (2002) paper and Glennan's (2002).

Russ et al. (2008) had designed a framework to analyse students' mechanistic reasoning in scientific inquiry. An observation was carried out during discussion among first-grade students about falling object. During the lesson, students were asked to predict what would happen if a book and a flat sheet were dropped at the same time from the same height followed by reasons. The study carried out by Russ et al. (2008) was a qualitative analysis to capture the coding schemes.

As Russ et al. (2008) stated that even young students could engage in substantive mechanistic reasoning when given the opportunity. As such, the researcher would like to explore students' mechanistic reasoning from different achievement levels. The data would be qualitatively analysed using observation, interviews and students' writing during the task. Comparing students' mechanistic reasoning will be conducted using Russ et al. (2008) analytical framework. How far students from different achievement levels could implement mechanistic reasoning will be conducted using card games and analysed qualitatively based on Russ et al. (2008) framework. A summary of the methodological aspects in mechanistic reasoning was shown in Table 2.3.

Table 2.3

Summary of Methodological Aspects in Mechanistic Reasoning

Author	**Methodology**
Ploger (1991)	- story generation, historical information and computer modelling method - First year of undergraduate students - Analyse qualitatively by merging all data (without framework)

Table 2.3 (Continued)

Schauble (1996)	- Study of scientific reasoning among 10 5th-6th grade children and 10 adults - Experimental design (Counterbalanced) - Analyse quantitatively
Abrams et al. (2000)	- Observation and interviews - Different region and different grades of students - Analyse qualitatively (without framework)
Machamer et al. (2000)	- The importance of discovery mechanistic reasoning using neurobiology and molecular biology work
Craver (2001)	- The role of mechanistic reasoning
Darden and Craver (2002), Darden (2002) & Glennan (2002)	- Strategies of mechanistic reasoning
Russ et al. (2008)	- Designing framework for mechanistic reasoning - Observation - Analyse qualitatively students mechanistic reasoning using framework
Current study	- Exploring mechanistic reasoning of students high achieving and low achieving - Observation, interview, students' written tasks. - Comparison between different achievement level - Using Russ (2008) analytical framework as a basis and further development of a 7-steps analysis.

Summary

The review of previous research presents two main arguments. The first is the problems that exist among students' learning biology. The difficulty in developing coherent understanding in biology is a common phenomenon throughout the world. Though past literature has provided the view of the problems or difficulties in learning biology, it still remains unsolved.

The second argument is that mechanistic reasoning is an appropriate paradigm in facilitating students to think outside the box. However, literature has showed that mechanistic reasoning is a higher order thinking skill that is not appropriate to be inculcated among low achieving students as they were often classified as less capable than the high achieving students.

The following chapter will discuss the conceptual and theoretical frameworks that would be employed to support the development of this study.