AMERICAN UNIVERSITY OF BEIRUT

MICRO-MACRO-SYMBOLIC INSTRUCTION TO ADDRESS STUDENTS' CONCEPTUAL CHALLENGES IN GENETICS

by
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ABSTRACT
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The purpose of this study was to first, identify year 1 International Baccalaureate (IB) students' misconceptions in genetics, and then investigate the effect of instruction that integrates the macro, micro, and symbolic representations and ontological aspects on addressing the identified misconceptions. The study aimed to answer the following research questions in particular: (1) What misconceptions do year 1 Diploma Program (DP1) students have regarding genetics? (2) What is the influence of a modified multiple level representation type of instruction that integrates the ontological aspect on the understanding and learning of the students? Twenty-three students from one class section in an American school in Kuwait participated in the study. The study used a qualitative design in the form of a case study. Participating students were chosen based on who consented to be part of the study from the DP1 class. The instruction lasted throughout the genetics unit which was around five weeks. The researcher was the teacher of the section that participated in this study. The instruction was centered on an ontological macro-micro-symbolic teaching approach that (1) focused on the interplay between the macroscopic, the microscopic, and the symbolic levels, (2) integrated the ontological aspects of concepts. Data sources for the study included a Genetics Literacy Assessment Items (GLAI) Test, a two-tier questionnaire, an extended response question (ERQ) and interviews to identify students' misconceptions, and two more consecutive GLAI tests, another two-tier questionnaire, 3 consecutive ERQs, and 3 consecutive interviews to evaluate the change of students' conceptual understanding of genetics. Pretest results indicated that students exhibited difficulties related to the transitions between particularly the macro and the micro levels and the ontology of genes. The consecutive tests showed that the students maintained these difficulties. This was largely due to the COVID-19 pandemic that happened when the study was being implemented and which impacted the duration of the study and the engagement of the students. However, the results of the study provide insight on implications for instruction in general and online instruction more specifically, curriculum development, and teacher education programs as well as recommendations for further research.

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CHAPTER I

INTRODUCTION

Over the past few decades, the challenges of teaching and learning genetics have remained a dominant topic in biology education (e.g. Johnstone & Mahmoud, 1980; Hackling & Treagust, 1984; Bahar, Johnstone & Hansell 1999; Osman, BouJaoude, & Hamdan, 2016). The science education literature has attributed the students' difficulties in genetics to: (1) The abstract nature of genetics phenomena and processes; (2) The intrinsic complexity of genetics- understanding of its major processes and mechanisms requires both to and fro thinking between molecular, cellular, organismal, and population levels (3) The incongruence between the level of difficulty of most genetics concepts and the cognitive level of students (4) The lack of prerequisite knowledge needed to promote the understanding of more advanced genetics topics, especially by middle school students, and (5) the incomplete understanding of genetics concepts resulting from previous instruction or informal sources, such as media and family (Osman, BoujJaoude & Hamdan, 2016).

This study focuses on addressing challenges due to the abstract nature and intrinsic complexity of genetics, denoted by reason (1) and (2), using a "multiple-representation-type" of instruction, otherwise referred to as "Macro-micro-symbolic representations". This instruction type has been mostly discussed and applied in the field of chemistry education with positive effects on students' learning and understanding. This study suggests that genetics and chemistry concepts share epistemological aspects that allow them to be pedagogically addressed in a similar manner such as the macro-micro-symbolic instruction. However, this study also acknowledges the differences between the two disciplines and the need to modify the

instruction to cater more specifically to the genetics concepts and proposes to do so by integrating an ontological aspect within the existing macro-micro-symbolic instruction. This modified instruction has been implemented on the genetics unit of the International Baccalaureate Diploma Program Year1 (IB DP1) high school students (equivalent to grade 11) and was evaluated based on its potency on improving students' conceptions.

Theoretical Background

In the last few decades, cumulative research on the process of learning has led to major changes in formal education, particularly in the understanding of what constitutes learning, and what the role of the educator encompasses. One can argue that the field of education has experienced a paradigm shift. Previously perceived as transmitters of knowledge in traditional learning, the role of educators has evolved under the new constructivist paradigm to be perceived as facilitators of learning instead (Tanner & Allen, 2005). Correspondingly, the role of students has changed from passive learners and mere "receivers of information" to active constructors of their knowledge.

The theories underlying this shift can be summarized by the following reasoning: individuals start to form their own understanding of the world from the moment they are conscious to its existence. This involves an ongoing process of deciphering surroundings in a manner that corresponds best with current understandings. This subjective process can become problematic once the individual enters the phase of formal schooling. When one enters the stages of formal education, the individual's own understandings are often challenged by what is taught in the classroom. The aim of formal schooling is to modify the individual's current understandings of phenomena, or what is referred to as *alternative conceptions* of reality into conceptions that align with what has been agreed on by experts across

different subject areas (language, math, science …) (Darling-Hammond, Flook, Cook-Harvey, Barron, & Osher, 2019, p.110).

Learning is no longer considered a passive absorption of information and facts, but an active construction and modification of present concepts from one form to another with the aid of the educator. According to the constructivists, as facilitators of conceptual change, educators must be aware of the pre-existing conceptions with which students enter the class and modify their method of instruction in a manner that targets those alternative conceptions. Growth of research revolving around applying different instructional approaches and strategies to improve the quality of learning and promote conceptual change in the classroom has consistently shown potential to promote better understanding and performance in comparison to traditional teacher-centered methods. Recent science education reforms have been guided by this shift in understanding of how learning happens and has been reflected in many educational policy documents (Tanner & Allen, 2005, p. 112).

Multiple-level Representations

Of the reoccurring perspectives in the science education literature is Alex Johnstone's (1982, 1991, 2000) emphasis on the potential of using different levels of representations in the science classroom instruction. Johnstone's focus has been mainly explored in the teaching of chemistry and addressing students' misconceptions in that subject. Through several articles, Johnstone attributes difficulties in chemistry to the nature of chemical concepts. He elaborates on how most chemical concepts can be defined/described at several levels, the macro, the micro and the symbolic. These three representations form the apices of the "learning triangle" (Figure 1.1) (will be referred to as Johnstone's triangle), and the sides of the triangle represent the connections

between these representations. Johnstone (1991) argues that both the apices, the multiple representations, and the sides of the triangle, how each representation relates to the other, need to be addressed in order to understand and learn concepts.

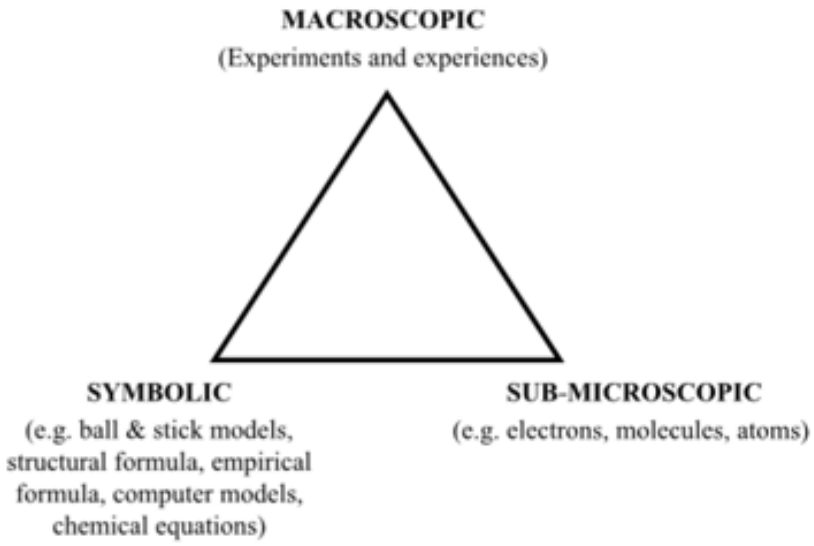


Figure 1.1. *The three representational levels in chemistry (Johnstone, 1991*)

The manner in which a concept can be represented by multiple levels of representations can be explained using the phenomenon of rusting. For example, rusting is a naturally occurring phenomenon that the individual encounters (rusting bicycle parts, jewelry, keys, etc.…) before he/she is taught about it in school. During early encounters, the individual might come to define rusting as a change in the color of an object from grey to red/orange. If the individual is particularly observant, he/she might conclude that this phenomenon happens when objects are left in storage or when left outside for a long time. This definition is conceptualized from the observable aspect of the rusting phenomenon.

At a more advanced age, probably after the individual has learned about this phenomenon in the science classroom, he/she comes to learn that rusting happens when

metals, particularly iron, react with oxygen and water. At an even older age, the student then comes to learn that the visible change in color that characterizes the rusting phenomenon is actually an outcome of events occurring between the particles of the iron, water and oxygen, and that these particles cannot be observed directly. At that point, the individual can describe rusting in two ways: the first being the color change, which is familiar and observable, and the other being the molecular/atomic description, which is based on abstract concepts (not observed by the student) to which the student is taught in class. These two different "ways" to describe rusting are actually representations of different levels that rusting can be described: the tangible/visible and the abstract/molecular.

Chemistry as a science can be described as a discipline that predicts and describes the interactions of atoms and molecules and the effect of this interaction on observable phenomena. Making a connection between these abstract sub-microscopic entities and tangible real-life phenomena requires the use of sophisticated mediators. In chemistry, these mediators are often chemical equations, mathematical formulas, constants and so on.

When the student is required to describe and explain rusting, he/she must be able to visualize this molecular aspect and link it to the familiar visible aspect to make sense of it. This is usually done through symbolic representations. These representations are not identical reflections of what is happening at the molecular level; however, they play a major role in initiating understanding of the unobserved and connecting the macro (red/orange rust) to the micro (molecular and atomic representations) (Johnstone, 1982, 2000). Johnstone emphasizes the significance of these (macro, micro and symbolic) levels of representation and highlights their role when understanding a particular concept.

In the aforementioned example on rusting, Johnstone's representations can be applied as follows: the student is prone to misunderstand the phenomenon of rusting if he/she cannot understand that the visible change in color of the iron when it rusts is due to the unobservable interaction between the atoms of the iron with oxygen and water in the air. This interaction forms a product, $Fe(OH)_3$, that we perceive as the "red" on the rusted iron. The student should be able to use chemical equations and symbols to represent the unobservable interaction. Rusting is when iron reacts with oxygen and water causing it to change color. This change in color is the macro representation of the rusting concept; it is visible and can be observed directly. The visible change is an outcome of the interaction between the iron particles, oxygen particles and the water. This interaction, which represents the micro aspect (or sub-micro as stated by Johnstone), happens at the molecular/atomic level that cannot be seen by the naked eye. To compensate for the inability to perceive it, a symbolic representation of this interaction is used to allow for its visualization. In this case, it could be a chemical equation; "$4Fe + 3O_2 + 6H_2O \rightarrow 4Fe(OH)_3$". Students can also rely on sketching "circles" as atoms to create molecules and visualize the chemistry of matter.

Applying Multiple-level Instruction

In consecutive research, Johnstone and other researchers focused on the potential of applying these levels of representations in the instruction of scientific disciplines. Most of these studies however applied this instruction to address challenges in chemistry (e.g. Becker, Stanford, Towns & Cole, 2015; Davidowitz & Chittleborough, 2009; Irby, Borda & Haupt, 2017; Jaber & Boujaoude, 2012; Treagust & Chandrasegaran, 2009). The instruction used focused on applying multiple-level instruction that focused on explicitly addressing the three representations and how they relate in the classroom.

These studies yielded positive results at varying degrees at different educational levels ranging across secondary levels up until graduate levels. The positive effect of integrating such methods in the chemistry classroom on students' understanding shown in these studies raises the question regarding the potential of these methods in addressing similar challenges in other subject areas. Especially since Johnstone already linked difficulties in science learning in general to the absence of these representations in the instruction and classroom discourse (Johnstone, 1991). Consequently, this study investigated the potential of applying the multiple representation instruction in the genetics classroom.

Challenges in Genetics

Studies conducted during the last two decades show that students find difficulty in understanding genetics (e.g. Bahar et al., 1999; Duncan, 2007; Duncan & Reiser, 2007; Knipples, Waarlo & Boersma, 2005; Osman, BouJaoude, & Hamdan, 2016; Shaw, Horne, Zhang, & Boughman, 2008). Many of the reasons investigated and difficulties identified in these studies can be linked to the multiple representations associated with the genetic concepts correlating to Johnstone's (1982, 1991, 2000) work on challenges in chemistry. This was highlighted in a study conducted by Osman, BouJaoude and Hamdan (2016) with Lebanese G7-12 students. The study showed patterns of misconceptions held by Lebanese students that were similar to their peers in other countries regarding genetics concepts including, "the nature of DNA, differences between gene and allele, proteins-phenotype relation, polygenic inheritance, role of the environment in modifying phenotypes, and plant genetics" (p. 1273).

The significance of these patterns is in how they reflect the students' difficulty in perceiving particular genetic concepts in more than one aspect. These difficulties align well with the difficulties in chemistry that were addressed by Johnstone's multiple

representation approach. In fact, molecular, cellular, organismal, and population levels present in the discipline of biology correspond to the *macro* and *micro* labels denoted in chemical concepts, where the molecular and cellular level can be considered microscopic, since they cannot be observed directly, while organismal and population levels can be considered macroscopic. Relating cellular to organismal would require some sort of symbolic representation; this can include utilizing sketches and diagrams in the classroom. Hereby, again, relating to Johnstone's perspective on the importance of different levels of representations for holistic understanding.

On the other hand, other studies that researched challenges in genetics attributed difficulties in genetics to the *ontological* aspect of the genetics concepts. *Ontology* deals with the classification of the entities of existence. Studies have shown that student challenges in particular topics could be attributed to the fact that they have categorized concepts of this topic under "inappropriate" ontological categories (Chi, Slotta, & Leeuw, 1994; Slotta & Chi, 2006). "Under the Incompatibility Hypothesis, it is the ontological status of a student's initial conception of such concepts which renders them difficult to learn, since acquiring the true conception requires a shift in ontological status" (Chi, Slotta, & Leeuw, 1994, p. 35). Hence, students' ontologies can play a role in perceiving a particular topic as challenging or not.

In this study, ontology was addressed to a limited extent as the focus was on the multiple-representation instruction. When applied to this study, an ontological aspect of a genetics concept is an aspect that defines what that concept physically is. For example, when describing the concept of "chromosome" ontologically, it would be identified as a state of the genetic material; it is a form of the genetic material that exists in a particular time during the cell cycle. The ontological aspect cannot be categorized as an "additional representation", as it does not add a new apex to the existing "multiple

representation triangle". Instead, it is arguable that the ontological aspect can offer the existing representations identified by the triangle a depth that is necessary when applying these representations to genetics.

To explain further the significance of identifying the ontological aspect in genetics the concept of a "gene" will be used. In the multiple-representation triangle, a gene should be categorized under the micro apex, as it is a microscopic entity: a strand of DNA. However, gene cannot be defined as being a strand of DNA, as not all DNA strands can be considered genes. This is because genes are characterized by their function in coding for particular traits. Hence, identifying a gene as a micro aspect does not encompass the full meaning of the concept. Duncan and Reiser (2007) argue that two ontologically distinct levels exist; those can be defined by the physical level, the physical existing entities and mechanisms, and the informational level, what information is carried by this entity. To elaborate on the example of the gene concept, an example of a gene coding for eye color will be explained both using the multiple representation triangle and the ontological levels. If the concept of "eye-color coding gene" were to be defined by the multiple representation triangle, the gene coding for the trait will be categorized under *micro,* the outcome, or the physical trait, will be categorized as *macro,* and the alleles used to describe the different forms of the gene will be categorized as *symbolic.* In this case, discussing the ontological aspect of the gene will aid in understanding the link between the *micro* and the *macro*. This is exemplified in the description by Duncan and Reiser,

> "To explain how genes can bring about an observable physical effect, such as brown eye color, one needs to account for the mechanisms that link the genetic information to the physical outcome. In the case of eye color, the gene encodes a protein that is involved in a cellular process that generates a chemical compound

(pigment) that makes the cells appear darker in color. Together, the cells color the tissue that makes up the iris of the eye, resulting in the perceived darker coloration of the eye." (2007, p.941)

In conclusion, parallels can be drawn between the difficulties perceived in chemistry and in genetics in regard to how both include concepts that can be represented at multiple levels. Studies in chemistry education that have addressed these challenges using instruction that explicitly defined concepts at the different levels of representation showed a positive influence on students' understanding and performance. Consequently, this study aims to modify these chemistry-related instructional methods to fit into the genetics discipline to address the similar challenges aiming to attain similarly positive results.

Purpose and Research Questions

Researchers in the field of chemistry education scrutinized chemical concepts and produced several studies that used instruction that explicitly defined and distinguished the multiple representational levels of these concepts. These studies presented positive results regarding the effect of such methods on improving learning and understanding (Jaber & Boujaoude, 2012; Treagust& Chandrasegaran, 2009). Similarly, research in biology education recognized similar challenges in genetics associated with the "multi-representational" nature of genetic concepts (e.g. Bahar, Johnstone & Hansell, 1999; Duncan, 2007; Duncan & Reiser, 2007; Knipples, Waarlo & Boersma, 2005; Osman, BouJaoude, & Hamdan, 2016; Shaw, Horne, Zhang, & Boughman, 2008). However, even though there is a rich archive of research on challenges in genetics and attributing these challenges to the multiple levels in genetics, there is a scarcity of research on designing and evaluating instructional methods to address these particular challenges. While it seems likely that applying such methods in

the classroom would be successful, it is important to have an abundance of studies on applying and evaluating those methods in biology and in genetics particularly. Such studies would provide insight on how to modify and improve teaching methods and evaluate whether the theoretical background of those methods has been accurately applied.

Consequently, the purpose of this study is to investigate multiple representation-type instruction as a method to teach genetics and address the challenges in learning genetics. Particularly, the purpose of this research study is to identify students' existing misconceptions and apply teaching strategies explored by Johnstone et al. (2000), to address those conceptions. The effectiveness of these strategies has been investigated in chemistry topics and yielded positive results. Since the issues addressed by this method in chemistry are very similar to those in genetics, there is a potential for this method to improve students' understanding of genetics.

To test this potential, this research study first aims to construct modified multiple representation instructional strategies in the context of genetics and then evaluate the effectiveness of such strategies in improving conceptual understanding of the topic by monitoring student's conceptual understanding of genetics throughout the study. Consequently, the questions addressed by this study are:

1. What misconceptions do year 1 Diploma Program students have regarding genetics?
2. What is the influence of a modified multiple level representation type of instruction that integrates the ontological aspect on the understanding and learning of the students?

This study is intended for year one International Baccalaureate Diploma Program Year1 (IB DP1) students at the standard level. The reasons for this choice are as follows:

1. The IB program is an international program applied across many schools all over the world. Implementing an instruction within this scope allows it to be one that can be applied internationally and not limited to a particular region's curriculum.
2. The IB has a syllabus with specified objectives for every unit (including genetics). The presence of such objectives limits the implementation of the instruction within the content specified IB requirements for the genetics unit. This is useful for a study implementing a new type of instruction, for it allows it to be tested and evaluated across a "manageable sample" of genetics content before attempting to implement in the sub-discipline as a whole.
3. Students taking IB Biology need to already have taken high-school biology (usually given the year before). Students that have taken high-school biology have an adequate knowledge of genetics as it is taught within the curriculum. This allows the researcher to see how the instruction affects existing misconceptions (prior to the implementation of the study) and how these conceptions change throughout the study. Furthermore, the material being familiar makes it more manageable for the student to follow the new instructions and the terminologies associated with this instruction (macro/micro/symbolic)

Rationale of the Study

The prevalence of the challenges that students face while learning genetics indicates that the topic is not being addressed in a manner that corresponds to its nature. This might correlate with the absence of instruction that explicitly addresses multiple representations in genetics. Ignoring the multiple representations makes it difficult for students to develop meaningful understanding of genetic concepts. This leads to the perceived complexity of the topic and the abundance of misconceptions. Johnstone

(1991, 2001) and other researchers have investigated similar patterns of challenges in chemical education and reached the same conclusion. Researchers then developed customized teaching strategies that explicitly address the different representations present for a given concept and evaluated the effect of these strategies. Results showed significant improvement in students' conceptual understanding.

However, as mentioned earlier, even though many researchers in the field of biology (Bahar et al., 1999; Duncan, 2007; Duncan & Reiser, 2007; Knipples, Waarlo & Boersma, 2005; Osman, BouJaoude, & Hamdan, 2016; Shaw, Horne, Zhang, & Boughman, 2008) have reached the same conclusion regarding the importance of addressing multiple representations in the discipline, the studies applying and evaluating customized instruction remain scarce. The scarcity of such work presents a gap in the literature of genetics education. Hence, there is a need for more studies that utilize present literature to design customized instruction to address present pedagogical challenges, and studies that evaluate these instructions to improve quality learning. Furthermore, this study will be one of the few studies that integrate both multiple representations and the ontological aspect in instruction. Results from this study will shed light on the potential of a novel approach to genetics teaching.

Significance of the Study

This study addressed challenges faced by students in genetics by integrating instruction that focuses on multiple representations and ontology of a given concept. Such approaches have shown to be effective in improving understanding in chemistry, and hence have potential in improving conceptual understanding in genetics. This study is significant in regard to it being one of a few) investigations that implement and evaluate instruction that addresses micro/macro/symbolic representations of genetic concepts, and implement and evaluate micro/macro/symbolic instruction whilst

addressing the ontology of those concepts. It provides insight to the practice of teaching genetics in general.

Implications to theory: Since most studies using macro, micro and symbolic representations have been applied in the context of chemistry; there is little or no established literature in the context of genetics regarding how to apply such representations. Hence, methods designed and used in this study can be used as models for future more sophisticated methods to teach genetics that researchers in science education can modify and improve based on the results. Furthermore, since there is scarce means of evaluating students' understanding in the context of multiple representations, the results of this study, which revolves mainly around genetics, open the door for research in other topics of biology and allow for exploration of more sophisticated modes of applicability.

Implications to practice: Design and instruments in this study could be used in the genetic lessons as part of instruction. This can apply in contexts of teacher training so educators can teach that topic in a manner that is explicit regarding multiple levels of representations, and the differences between those levels and on how and where to start with these levels so that the student starts with a representation that he/she deems familiar and can transition smoothly into newer zones. Furthermore, results of the study can guide curriculum developers in what aspects to focus on when designing the material to be taught, and what sequence would give the students the best start to recognize, define and distinguish between different levels of representations of a particular concept.

CHAPTER II

LITERATURE REVIEW

This study focuses on designing, employing and evaluating an instructional approach in the biology classroom throughout the unit of genetics at grade 11/ IB DP1 level. This instructional approach is a modified macro/micro/symbolic representation instruction, that not only integrates defining genetic concepts at the three levels of representations and relating them, but also defining these concepts ontologically in the aim of enhancing students' understanding and addressing their challenges in the topic.

The micro/macro/symbolic representation instructional approach has been cited in many papers as an effective method to address challenges in the science classroom, particularly in the subject of chemistry. This chapter brings forth research that supports that concepts within the discipline of chemistry and genetics share a similar nature that may make these topics challenging for students. Hence, this chapter proposes the argument that due to the aforementioned similarity, these challenges can be addressed in a similar manner; hence an instructional approach proven effective in addressing challenges in chemistry has potential in addressing those in genetics.

Similar to the cited micro/macro/symbolic representation instruction, the study aims to implement an instructional approach that focuses on explicitly defining genetics concepts within the scope of the macro/micro and symbolic levels whilst being explicit regarding how these levels relate. However, to address epistemological differences between chemistry in general, and genetics as a sub-field in biology, the instruction adopted has been modified to accommodate the topic of genetics, and hence the ontological aspect has been integrated within the instruction along with the three levels of representations.

In this chapter, relevant conceptual and empirical research are presented in context of this study which includes theoretical aspects of the macro/micro/symbolic instruction that

have been mostly explored in chemistry and the results of applying such an instruction. Furthermore, this chapter also explores the nature of genetics as a topic and the consequent challenges of such a nature paralleling difficulty in chemistry and genetics. Finally, this chapter identifies differences between the disciplines and argues for the integration of the ontological aspect within the Macro/Micro/Symbolic instruction to address these differences.

Macro/Micro/Symbolic Instruction

Alex Johnstone's research on the significance of using multiple levels of representations in the classroom to explain a particular concept, or Johnstone's triplet, have been a re-occurring topic in the science education field. Johnstone (1991) attributes difficulties in science, amongst other reasons, to the multilevel nature of scientific concepts. He elaborates how science includes many concepts that often cannot be directly detected by the senses and hence scientists often have to rely on experimentation and modeling to understand such concepts better. While modeling and experimenting might allow for the visualization of certain aspects of the concept, they most definitely do not succeed in creating an exact visual of this concept (Johnstone, 1991).

Johnstone elaborates on the difficulty of the sciences due to these unobservable aspects of most scientific concepts by specifying how not only can these concepts be represented by multiple representations, but these representations can be categorized into "levels of thought" referred to as "macroscopic", "sub-microscopic" and "symbolic". While these multiple levels of representations might be understood by the educator, the student, who is a novice in the field, would often be limited to one or two levels, and even if he/she is aware of those multiple levels, he/she often cannot form the link between them or relate them in context of the concept (Johnstone, 1991; Marbach-Ad & Stavy, 2000). Johnstone (2000) then elaborates these points in the context of chemistry addressing challenges students face in the subject. According to Johnstone (2000),

> the nature of chemistry exists in three forms which can be thought of as corners of a triangle. No one form is superior to another, but each one complements the other. These forms of the subject are (a) the *macro* and tangible: what can be seen, touched and smelled; (b) the *micro*: atoms, molecules, ions and structures; and (c) the *representational*: symbols, formulae, equations, molarity, mathematical manipulation and graphs (p. 11).

Johnstone illustrated those forms in Figure 2.1 in one of his older papers (1991).

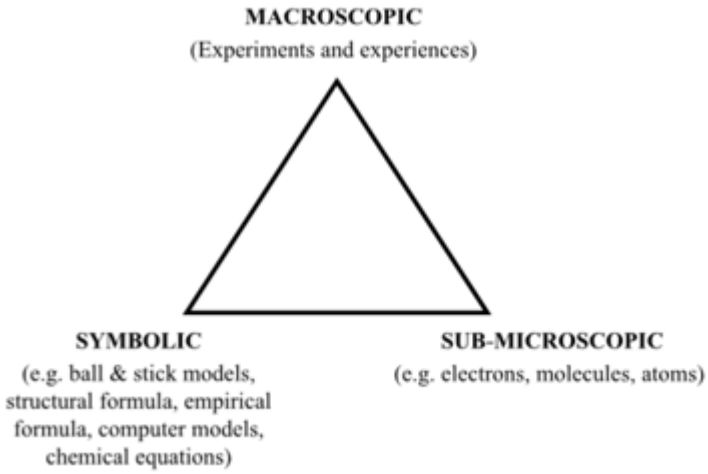


Figure 2.1. The three representational levels in chemistry (Johnstone, 1991)

To understand the nature and mechanism of chemical reactions, one cannot limit a given phenomenon to what is observed only or perceived by the senses, such understanding would be incomplete. More importantly, one must also be able to visualize the *micro* situation where substances interact to cause the visible phenomena (macro). Since these interactions are neither visible nor tangible, they must be represented in a tangible form that can be manipulated by students. When the student is required to describe and explain a chemical reaction, he/she must be able to visualize this molecular aspect and link it to the familiar visible aspect to make sense of it. The *symbolic representation* is the educator's tangible interpretation of the abstract *micro* phenomena and is usually used to connect the micro and the macro aspects of a concept.

Application of Macro/Micro/Symbolic Instruction

Around two decades after being introduced by Johnstone, these representations were still being discussed, applied, and evaluated in their efficacy in addressing challenges in scientific concepts. Similar to what Johnstone has discussed in his papers (1982, 1991,2 000), researchers have argued that when studying several chemistry concepts, students do not holistically understand these concepts unless they are aware of these three representations and how they are connected. For example, to understand chemical reactions, students should be able to link the macroscopic, which is the visible aspect of the chemical change with the underlying re-arrangement of particles that is simultaneously occurring at the sub-microscopic level whilst understanding the symbols used to denote these unobservable changes (Treagust & Chandrasegaran, 2009). This perspective was reiterated in many bodies of research done at different educational levels and across different chemistry sub-disciplines.

Treagust and Chandrasegaran (2009) conducted a study which aimed at developing and testing an alternative instructional program aimed at secondary students (particularly ninth graders) on the topic of chemical reactions. This instruction incorporated multiple representations in the instruction for a period of seven months, and results showed that students who underwent the alternative program showed higher proficiency in the topic than the control group that was not exposed to the multiple representation instruction.

In a more recent article, also implementing multiple level representation instruction to teach chemical reactions but for secondary school students at the tenth-grade level, Jaber and BouJaoude (2012) found similar results. In their study that aimed to promote better understanding in chemistry, particularly in understanding of chemical reactions, Jaber and BouJaoude (2012) designed lessons that explicitly integrated the macro-micro-symbolic representations of the chemical reactions studied. The integration of the multiple levels in the

instruction was described as follows: in a lesson on determining the type of chemical reaction, the teacher involved the students in the following activities,

1. First, engaging the students in a demonstration of a chemical reaction (e.g. adding hydrochloric acid to silver nitrate solution).
2. He then asked the students to describe what is happening in the demonstration based on observable changes perceived (macro). When the students were told to describe what they saw, the teacher integrated the term *macro* to refer to the observable phenomena.
3. Then, students were encouraged to write the chemical equation of the reaction so that they connect their observations (macro) to the symbolic representation of the reaction.
4. Afterwards the students were asked to interpret their observations at a microscopic level and to use symbols to represent the reaction. (Jaber & BouJaoude, 2012)

Throughout instruction, the teacher would use the terms *macro, micro* and *symbolic* for the task at hand to illustrate how different activities correspond to describing a specific level. The lessons focused explicitly on distinguishing between the three different levels of representing the same chemical reaction. More importantly, they also allowed the students to connect the three levels to one another: macro to symbolic, macro to micro, then micro to symbolic.

While the study by Jaber and BouJaoude (2012) was much shorter than that of Treagust and Chandrasegaran (2009) , with a duration of five weeks, the study showed a significant improvement in the conceptual understanding and relational learning of chemical reactions for students who were exposed to the multiple-level-type instruction. The findings of this study indicated that integrating instruction that defined and distinguished among the three different representations “foster[ed] [the students’] relational reasoning, and hence

help[ed] them develop a more integrated conceptual knowledge in chemistry" (Jaber & BouJaoude, 2012, p.991).

Davidowitz and Chittleborough (2009) found that encouraging undergraduate students to draw and annotate diagrams representing sub-micro phenomena enhanced their understanding of the macro aspect of the concept and how they relate, and ultimately improved the students' performances. These diagrams were applied to aid students in setting foundations in concepts such as atoms and molecules, elements, compounds and mixtures, and extended to apply to topics such as the mole concept, stoichiometry, solubility and chemical equilibrium.

Becker, Stanford, Towns and Cole (2015) emphasized the role of the instructor in guiding the classroom discussions to address the multiple representations and hence enhancing students understanding in an undergraduate physical chemistry course on thermodynamics. Irby, Borda and Haupt (2017) found that by incorporating the multiple level-instruction within virtual lab models in a general chemistry course, students at a master's granting university were more likely to link the different representations and perform better in the topic.

These different bodies of research support the notion that integrating multiple representation type instruction supports student learning in the classroom through enhancing their conceptual understanding. These articles are valuable not only in how they support the use of such instruction, but also in providing different ways to apply such an instructional approach, perhaps providing insight as to how to apply this instructional approach in other disciplines as well.

The Nature of Genetics and Consequent Challenges in the Classroom

The difficulty of teaching genetics has been one of the most reoccurring issues in biology education in the last decade. This is relevant not only because it is an educational

challenge, but also due to the rising importance of genetics literacy in our modern time. According to Stern and Kampourakis (2017, p.194),

> Genetics literacy is a demand of our times because the related knowledge can have a direct impact on our everyday lives…[hence]… it should be a central goal for science education to educate future citizens who will be literate about genetics. We live in the post-genomic era, the era after the completion of the sequencing of the human genome, during which powerful new DNA sequencing technologies are available.

Genetic literacy can be defined by several outcomes, a key aspect defined by Duncan, (2007) is understanding how genes and particular genotypes lead to the trait they code for, and hence understanding why certain mutations bring about dysfunctions (such as sickle cell anemia caused by a single base substitution). In other words, students should be aware of the sub-cellular and cellular processes that translate a particular gene to the trait for which it codes.

There is a consensus in the literature that students perceive genetics as one of the most challenging biology sub-disciplines (e.g. Bahar, Johnstone & Hansell, 1999; Duncan, 2007; Knipples, Waarlo & Boersma, 2005; Osman, BouJaoude, & Hamdan, 2016; Shaw, Horne, Zhang, & Boughman, 2008). Interestingly, one can draw parallels from the literature regarding difficulties that students face in genetics, and those addressed in chemistry using the multiple representation instruction. Hence, after reviewing papers regarding challenges in genetics, this study proposes that these challenges can be addressed with a modified multiple level representation instruction that corresponds to the nature of genetics and the prerequisites of genetic literacy.

Bahar *et al*. (1999), attributed difficulties in genetics to the complex nature of the concepts within this topic. This nature aligns with Johnstone's description of chemistry concepts (1991, 2000) on how concepts exist in more than one representational level and how

not all these levels are addressed in the classroom, or the links between these levels is not established. Bahar *et al.* specify that genetics concepts involve, "three different thought levels: the *macro* (tangible), the *micro* (or sub-micro and molecular), and the *representational*" (p.86). These correspond to the terms set by Johnstone and referenced earlier in this chapter. Bahar *et al.* explain the challenging nature of the multiple leveled genetics concepts by giving examples of common approaches in the genetics classroom. Such approaches include relating concepts such as "genes" and "alleles" directly to physical characteristics/traits to establish how organisms are the outcome of their genetic makeup. For example, students are taught that a particular gene is responsible for controlling a particular trait without knowing how such control is established.

The issue with this approach is, as elaborated by Bahar *et al*. is that using, "genes, alleles and so on to explain the *macro* (what is accessible to the senses/observable) takes students into the *sub*-micro (cellular/sub-cellular), which is not directly accessible to the senses. The sub-micro is then represented and manipulated by symbols and mathematical devices which are *symbolic* of what is happening at the *sub-micro"* (p.86). This is done without explicitly distinguishing between the different levels of representation, nor establishing the connections between each. Furthermore, students cannot alternate between the concept of a gene and its outcome (the trait; the phenotype) if the microscopic processes of how one leads to other are not addressed, and if it is not explicit which concepts are symbols.

To elaborate further the problematic nature of such approaches as argued by Bahar *et al.*, assume eye color is a trait determined by a single gene. Depending on the particular sequence of nucleotides (DNA monomers) of that gene, or the different alternatives of that gene (also referred to as *alleles*), a particular protein would be produced, and that protein would trigger reactions that would lead to the particular eye color outcome. DNA, proteins

and the mechanism in which the proteins eventually lead to the determining of the eye color all molecular/cellular (micro) concepts. The only observable (macro) aspect of this would be the eye color which is the result of the aforementioned micro aspects. Furthermore, the ontological aspects of the aforementioned terms are rarely addressed either, which is an issue that will be addressed in more detail in upcoming sections.

The issue highlighted above parallels the challenges cited in the chemistry education literature and addressed using multiple representation-type instruction. Similar to chemistry, genetics has underlying microscopic components and processes that ultimately influence observable entities, and one cannot explain why these observable traits arise without understanding what happens at a microscopic/sub-cellular and cellular level.

Correspondingly, a study by Osman, BouJaoude and Hamdan (2016) with grade 7 to 12 students also attributed the difficulty in genetics to similar reasons in how the "abstract nature of genetics phenomena and processes" and the "intrinsic complexity of genetics itself [involves] to and fro thinking between molecular, cellular, organismal, and population levels" (p. 1259). This was demonstrated in the interviews that revealed, "a low level of progression in the conceptual understanding of major genetics concepts, specifically the microscopic, macroscopic relation between gene and trait…genotype, and phenotype" (p.1270)

The terms "molecular, cellular, organismal, and population" correspond to Johnstone's multiple representations, where the molecular and cellular level can be considered microscopic while organismal and population levels can be considered macroscopic. Relating sub-cellular and cellular levels to the organismal levels would require a representation that would help the students visualize the unobservable to relate it to the observable, which is the role of the symbolic representation. Furthermore, concepts of genotype and phenotype can also be linked to microscopic and macroscopic representations

where alleles represent the symbolic aspect. Hereby, again, relating to Johnstone's perspective on the importance of different levels of representations for holistic understanding.

The Nature of Genetics and Ontology

Another model of levels of representations is proposed by Duncan and Reiser (2007) that goes beyond the corners of Johnstone's triangle. They propose that even though biology and chemistry both have concepts that exist in multiple levels, the multiple levels in biology are hierarchical where, "that elements at one organization level constitute the elements of progressively higher organization levels; for example, cells constitute tissues, which in turn constitute organs"; this encompasses the sub-discipline of genetics. Consequently, "understanding genetic phenomena entails understanding how mechanisms and interactions at the molecular (genes, proteins) and microlevels (cells) bring about effects at the macrolevel (organism, population)" (p.939).

The importance of explicitly defining the terms in genetics cannot be simplified by merely labeling the terms as macro, micro or symbolic. The educator must delve into the nature of *ontology*, or the nature of being/existing of these concepts. Whilst ontology in not an aspect mentioned in Johnstone and related literature, it is a significant aspect in the genetics context.

For example, when addressing the term gene, which is the basic unit of heredity, Johnstone may argue the gene belongs under the sub-microscopic level, since it is an entity that exists microscopically and cannot be observed directly. However, taking into consideration the ontological aspect, the term gene can mean several things depending on the context discussed. Duncan and Reiser (2007) distinguish between the multiple meanings within the term gene.

> the term gene can be used to denote both a unit of information (the gene for a particular trait), and a physical segment on the DNA molecule. The physical DNA sequence is

important for the replication of the genetic material (during cell division) and regulation of gene expression (turning the gene on and off) as the molecules that control these aspects of gene function need to interact with the DNA itself (Duncan & Reiser, 2007, p.940).

Figure 2.2 shows the *hybrid hierarchal model* proposed by Duncan and Reiser (2007) to describe how the concepts within genetics are organized. This model shows that not only are concepts within the discipline organized in a hierarchal manner, but rather in a hybrid form of such. This is because within one level, divisions may form depending on the ontological aspect of the concept (as shown in Figure 2.2**.** when describing the function of a gene)

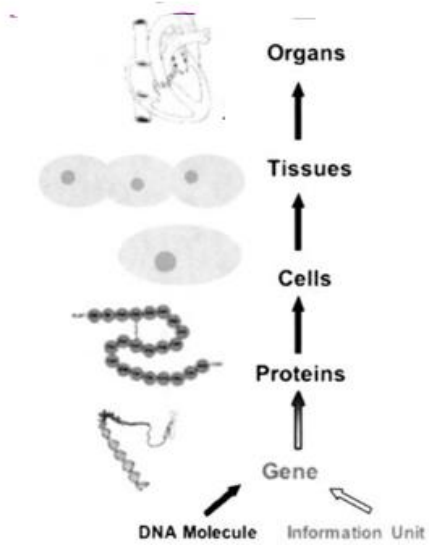


Figure 2.2. The hybrid hierarchical structure proposed by Duncan & Reiser (2007)

To elaborate, this model includes an *information level* and a hierarchically organized physical *level* of the term "gene".

Hence, it has been established that genetics involves terms that can be defined at multiple levels within the levels earlier discussed by Johnstone, and these levels can be addressed by integrating the ontological aspect of the concept as shown by **Figure 2.3.**

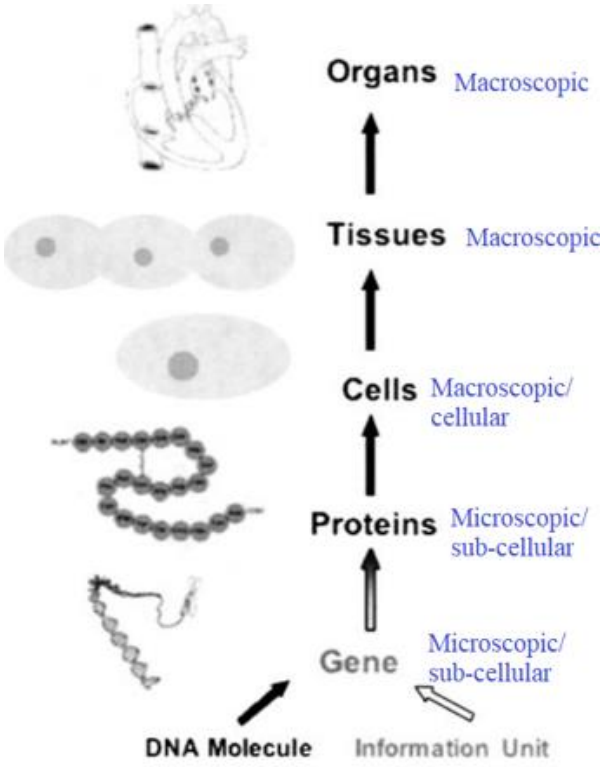


Figure 2.3. The hybrid hierarchical structure proposed by Duncan & Reiser (2007) in context of Johnstone's multiple representations

Knipples, Waarlo and Boersma (2005) also attributed student difficulties in genetics largely due to their misunderstanding of the genetics terminology which is a prerequisite to solve any classical genetics problem. The study also shows how some students seem unaware of what a Punnett square represents. In the study, "[the student did] not appreciate that the Punnett square depicts the possible gametes from the parents bearing the given trait" (p.110). Students are excellent at figuring out the outcomes when given the Punnett square to fill, but when asked what is represented on the axis, or when challenged on constructing their own Punnett squares, they are lost. They fail to realize that the purpose of the square is to act as a

tool to predict the probability from the parental genotypes. The connection between meiosis, as a molecular process (micro) and the Punnett square as a tool to predict the genotype of offspring (symbolic) should be made explicit. Particularly emphasizing on what aspects of the genetics terms are represent an actual existing entity and which are inventions to manipulate and predict outcomes. The possible gametes from the parents bearing the given trait.

In summary, each parent, will have their sex cells go through meiosis, meiosis will result in four non-identical cells that have half the number of chromosomes. In humans this means that instead of having the two versions of a gene (maternal/paternal for nose length), the outcome of the meiotic division will have one version only, hence carrying one allele (demonstrated in Figure 2.4). The illustration shows how the cell first carries two versions of a particular gene (versions denoted by "A" and "a") and how through meiosis, the gamete ends up with one version only (could be either). Each of the four sex cells carries a particular version/allele, and since each meiosis results in four sex cells for every parent, and sexual reproduction involves (usually) the fusion of one from each, this means that any one of the four gametes from one parent could fuse with any of the four from the other parent. All the aforementioned description is of microscopic processes that occur in adult male and female bodies. The consequence of these processes cannot be directly observed unless the cells are extracted, and DNA is sequenced for every single sex cell. The only observable aspect of this process is the offspring, which is the outcome of the fusion of a random sex cell from each parent. Hence the need for the Punnett square as a predictive tool. Punnett squares can arguably fit under the "symbolic" criteria set by Johnstone; however, it is important to explicitly define it as a symbolic tool, rather than a symbolic representation of an existing entity.

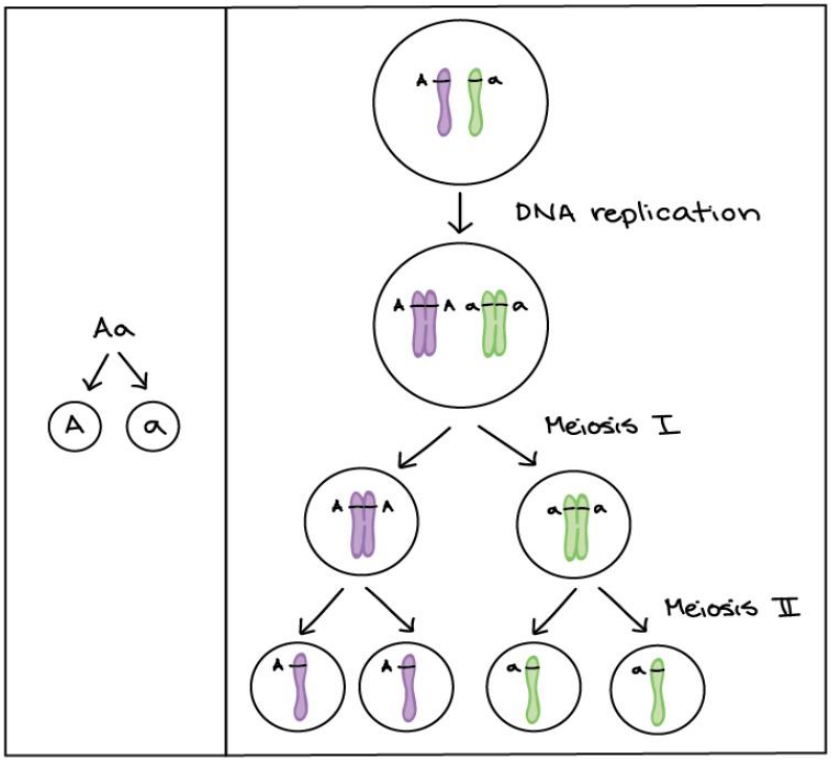


Figure 2.4. One parent sex cell going through meiosis to produce a gamete that will fuse with the other parent's gamete form the zygote[1].

Punnett squares are tools to predict the outcome of this fusion using the alleles from each parent, it is not a physical entity nor an ongoing process (demonstrated in Figure 2.5). Gametes of each parent are on separate axis of the square, while the offspring are on the four quadrants of the square. The letters "A" and "a" denote the alleles of a particular gene. "A" represents one outcome (i.e. big nose) while "a" represents the alternative outcome (i.e. small nose). Punnett squares do not physically exist; they are an invention, tools that use **symbols** to predict genotypes.

1 (Adopted from *Khan Academy* "The chromosomal basis of inheritance", n.d. Retrieved October 29, 2018, from https://www.khanacademy.org/science/biology/classical-genetics/chromosomal-basis-of-genetics/a/discovery-of-the-chromosomal-basis-of-inheritance.)

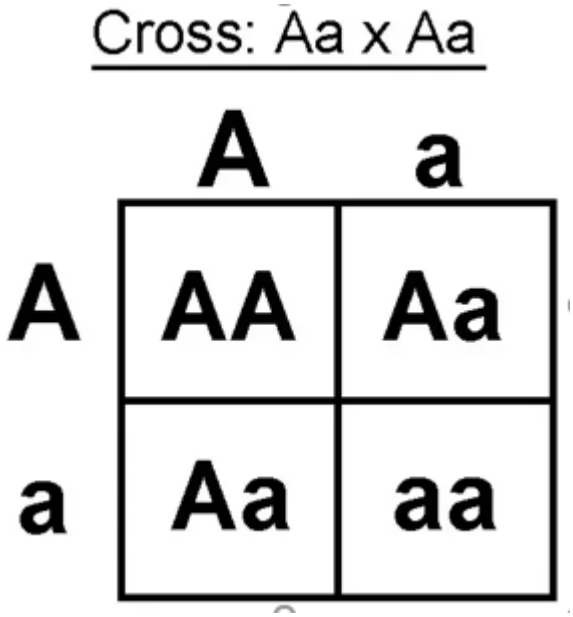


Figure 2.5. Punnett Square denoting the potential outcome (of offspring) when the gametes of parents carrying the gene denoted by "Aa" fuse.

The absence of such understanding of these processes means the student has failed to connect the different terms and processes. According to Knipples, Waarlo and Boersma, "when students fail to form the connection between what happens during meiosis, the resulting gametes, and chances of different outcomes of the fusion then, the Punnett Square becomes a biologically meaningless diagram and tool and hence correctly solving one is not an indicator that the intended concept has been acquired" (2005, p.110).

According to (Chi, Slotta, and Leeuw (994, p. 42), "The Incompatibility Hypothesis about learning asserts that concepts for which the veridical ontological status and the students' conception are incompatible will be more difficult to learn, than those concepts whose ontological status between the vertical and the naive conceptions are compatible." This hypothesis correlates with aforementioned research on student difficulties in genetics relevant to inconsistent ontologies. In a study conducted by Slotta and Chi (2006), when students were trained to ontologically categorize physics concept, they were more receptive to the lesson and harbored a deeper understanding of the concepts presented in comparison to

a control group that was not exposed to the ontological preparation. This suggests that addressing the ontological aspect of concepts can enhance the students' learning experience to a significant extent. However, it is important to note that in this study, the ontological aspect of concepts was not emphasized, as the focus was on multiple representations. Instead, the students were briefly be exposed to ontological aspects by being encouraged to categorize the concepts as "real/unreal" or as "matter" vs "process".

In summary, this chapter established the similarity between chemistry and genetics in regard to how concepts in both disciplines can be represented by multiple levels and how this nature makes these disciplines challenging to the students when these levels are not explicitly addressed in the class. Similar challenges arise when these representations are addressed but without explicitly explaining how they contribute to defining the concept they represent. Furthermore, several research articles supported Johnstone's multiple levels and their significance in addressing these challenges, with several studies proving that integrating such instruction enhances student understanding and learning. These studies suggest that such methods have a potential in addressing concepts of complex nature such as genetics. This chapter then delved into the nature of genetics concepts as cited by several references, and the levels that these references distinguished for genetics. Even though there was an alignment between those levels and the ones set by Johnstone, an important distinction was the hierarchal nature of the biological levels. This nature can be addressed whilst still using Johnstone's model by integrating an ontological aspect within Johnstone's three representation levels. Hence, this study aims at applying multiple-representation-type instruction within an ontological context by defining genetics terms explicitly in the context of Johnstone's multiple representations whilst adding the ontological dimension of the concept.

CHAPTER III

METHODOLOGY

The purpose of this study is to investigate year one International Baccalaureate (IB) Biology (standard level) students' misconceptions in the topic of genetics using an instructional approach that focuses on the "macro/micro/symbolic" representations and ontological nature of genetics, and to investigate the influence of such an instructional approach on the students' learning and understanding of genetics. Specifically, the study aims to address the following research questions.

1. What misconceptions do year 1 Diploma Program students have regarding genetics?
2. What is the influence of a modified multiple level representation type of instruction that integrates the ontological aspect on the understanding and learning of the students?

The first question requires using diagnostic instruments to determine existing conceptions that the students hold. Preliminary tests will be administered prior to the onset of the instruction to determine the students' baseline knowledge and the nature of their conceptions of genetics. These instruments are discussed in the upcoming sections. For the second research question, several instruments are used throughout the study to provide insight regarding the effect of multiple level representation type of instruction on the learning and understanding of the students, and from these instruments, this study evaluates the effectivity of the instruction in regards to addressing in improving student understanding of the topic.

In this chapter, the setting in which this study is implemented is described to give context on the study's participants. Furthermore, this chapter addresses the design of the study and the method of implementation including what instruments were used and how will these instruments be analyzed to address the study's research questions.

Study Site and Participants

The study was conducted at a private international school in Kuwait, hereafter referred to as The Academy. The Academy is a school with a large population constituting of three campuses, two in the area of Hawally, and one in the area of Salmiya. Both Hawally campuses have classes from Kindergarten to grade 12; one campus is for boys and one for girls. The Salmiya campus is divided so that the boys and girls are segregated, and it has classes from kindergarten to grade nine. The school student population across the three campuses is mainly Kuwaitis, whilst teachers are mostly non-Kuwaiti.

As of 2019, The Academy has been awarded dual re-accreditation status by the Council of International Schools (CIS) and the Middle States Association of Colleges and Schools (MSA). The Academy has also been awarded re-accreditation by the International Baccalaureate Organization (IBO) in 2015. The Academy offers the Diploma Program (DP) curriculum (for students aged sixteen to eighteen) of the International Baccalaureate. The students have the option to become diploma students of the International Baccalaureate (IB), which means they take the full IB DP program, or to become certificate students which means that they take one or more DP courses without having to complete the extracurricular DP requirements. Those who choose to take the IB diploma program graduate with two degrees, the IB diploma and the Academy diploma (American curriculum). Those who choose to take only a number of IB courses, or no IB courses at all graduate with The Academy diploma only.

The IB biology standard level program is a two-year program for students aged sixteen to eighteen that covers a wide spectrum of topics. In the first year of the program, the students study four out of the six required topics in biology: Cell biology, molecular biology, genetics and ecology. The genetics topic includes five sections that focus on: genes, chromosomes, inheritance (Mendelian genetics) and genetic modification (refer to **Appendix**

1 for the IB syllabus). The genetics unit is typically given during the second semester of the first year, after the students have covered cell biology and molecular biology. These topics discuss building blocks of DNA (nucleotides), DNA related processes such as DNA replication, transcription and translation, all of which can be considered as pre-requisites for understanding genetics.

The study was conducted at the boy's campus of The Academy in Hawally. Participants of the study were twenty-three eleventh grade boys, aged sixteen and seventeen, both diploma students and certificate students taking IB biology at the standard level (SL, students referred to as DP1 biology SL students). The Academy students take biology during the whole school year of grade 10 and cover a genetics chapter. The genetics content taken during tenth grade introduces most of the concepts required in the IB biology genetics curriculum; hence, participants were familiar with most of the content to be covered except for some details. All the participants were returning students and hence all of them had a background in genetics from the last year. Furthermore, it is important to note that in every grade level, the Academy has an honors class section that takes higher and more challenging content than the other sections. Particularly in grade 10, students in the honors section study content that prepares them for the IB courses in the upcoming year (even if they do not intend on taking IB classes). Hence, some participants in this study had an advantage over the other students because they were part of the "honors" class in the previous year. These discrepancies between students' prior knowledge were taken into consideration, since the students were evaluated before the genetics unit, during and after, the focus was on the development of students' understanding of the genetics concepts rather than comparing their understanding amongst each other.

Design

The focus of this study is to examine how using an instructional approach that defines the different representations of concepts in the multiple level and the ontological scope influences students' learning. Since this study focuses on the influence of an instructional approach on a particular process (learning), and learning is a partially individualistic type of process it lends itself to a qualitative research design in the form of a case study. This is to give insight regarding several individual's processes of learning genetics with the aim of reaching a general conclusion on how such an instructional approach influences students' understanding. A qualitative design was chosen due to the ability of such a design "to answer questions about experience, meaning and perspective, most often from the standpoint of the participant" (Hammarberg, Kirkman, & Lacey, 2016, p.499). Since this study focuses on the learning and understanding of students and how these are influenced by a particular instructional approach, a qualitative method provides insight regarding this process amongst several individuals, consequently evaluating whether this instruction enhances student understanding of genetics concepts.

This study aimed first, to identify and characterize Year 1 Diploma Program (DP1) biology SL students existing conceptions in genetics (addressed by the first research question), then evaluate the influence of "macro/micro/symbolic instruction" on these existing conceptions and how these conceptions change (addressed by the second research question). Hence, students' conceptions need to be evaluated before, throughout, and after the instruction to monitor the conceptual status.

The implementation of the instructional approach intended to last throughout the unit of genetics, which usually spans around four weeks. There are five hours of biology teaching per week, totaling around twenty instructional hours, which is more than what is recommended by the IB curriculum for the genetics unit (Diploma Program, Biology Guide,

2016), however it is still within the scope of what is limited by the sequence and planning done at the first IB meeting in the school year. The reason why the time is more than what the IB recommends is to ensure that the students would not be overwhelmed or rushed with the introduction of the new instruction whilst being introduced to new content. In other words, the unit was given more than the recommended instructional time because the content was being introduced with a new instructional method. However, the span of the study was different than the aforementioned given circumstances that will be discussed and elaborated in the upcoming chapter.

Since this study was implemented in an IB-Biology class, the IB biology guide was used as the unit's syllabus as it provided the objectives and understandings for every section of every chapter/unit, including the chapter on genetics. Hence, the content of the genetics unit has already been defined and specified in the IB curriculum (Diploma Program, Biology Guide, 2016). Therefore, the instruction focused on covering the required content and objectives whilst addressing the different representations and ontological meaning of the required concepts.

The educator who implemented the study was the researcher herself. The researcher has had two years of teaching experience, both of which were in IB biology. The researcher has a bachelor's degree in biology along with a secondary teaching diploma in science education and an ongoing master's degree in science education. Since the larger purpose of this study was to create an effective instructional approach that can be applied by any IB biology teacher to make genetics more comprehensible, the researcher acknowledged the possible negative effects on the study's validity by applying the instruction herself, and discussed the measures taken to conserve the validity of the results and data in the previous section.

This study aims at addressing student misconceptions and improving them through an instructional method that focuses on addressing the multiple representations present within a concept. As a result, students were encouraged to categorize concepts within the Johnstone triangle, and to reflect on the ontology of these concepts through class discussions and activities.

Implementing the Study

In this section, the details of applying the study in the classroom are discussed.

Defining the Terminology

This study involved implementing an instructional approach deemed effective in chemistry to the context of the biology classroom. Consequently, terminologies such as microscopic, macroscopic and symbolic used in chemistry were modified and explicitly defined at the beginning of the study to fit in the biological concept. Even though they have been defined in related studies, applying those terms in a novel context required adjusting those terms accordingly, and hence the purpose of this section.

The Micro Component. In this study, all *microscopic* and *sub-microscopic* entities and concepts were categorized under the micro category. This included entities that could be directly observed under the microscope. The argument here is that even though these concepts can be directly observed, they still require a tool or instrument and hence cannot be perceived by the senses directly and are not always immediately observable. The microscopic category also included concepts/entities that are too small to be observed under the microscope including: DNA, genes, and nucleotides. Furthermore, this category also included microscopic processes such as mitosis and meiosis.

The Macro Component. In this study, all concepts that could be directly observed by the senses such as physical traits, symptoms and conditions of diseases were categorized under the macroscopic component.

The Symbolic Component. All concepts categorized under the term *symbolic* were concepts that "did not physically exist". Included under this category are sketches of nucleotides that are used to facilitate the understanding of Nucleic Acid structure and alleles, (represented as letters) and Punnett squares which are used as instruments to predict patters of hereditary. Sketches of cellular processes were also considered symbolic representations.

The Ontological Component. As defined in Chapter I, *ontology* deals with the nature of and the classification of existence. In genetics, an ontological aspect is an aspect that defines what the nature of the concept is. Is it like a chromosome where it physically exists? Is it a predicting tool such as the Punnett square? The ontological aspect gives the multiple representations a depth that is necessary when applied to genetics- that differs from chemistry.

Students were not expected to understand or categorize concepts under the "ontology label". However, they were encouraged to reflect on the nature of the concept through guiding questions and instruction. Students were asked questions such as, "does [this concept] exist?", "can I physically locate it?", and if not "why do we use it". Some symbolic concepts are direct representations of microscopic concepts (formulated to create a visual representation of an otherwise "invisible"(cannot be observed directly) concepts), other symbolic concepts are instruments used to manipulate or represent outcomes of microscopic processes such as the Punnett square, which is a symbolic tool to predict offspring outcome from parents.

Students were encouraged to categorize the genetic concepts through multiple strategies including supplementary material (discussed later in this section) and class instruction. At the beginning of each section, the students were asked to categorize all concepts of the section into the micro/macro/symbolic categories from the beginning of the

lesson to indulge in organizing the concepts as a “preparation” activity through the supplementary material.

Instruction

The following section describes how the instructional approach was implemented through the sequence of the unit and how supplementary tools were used to aid in instruction. The instructional approach is elaborated through the use of a sample lesson as an example. Furthermore, the nature and purpose of the supplementary material will be discussed.

The instructional content followed the sequence outlined in the genetics chapter in the IB Biology syllabus guide (outlined in **Appendix 1**). The genetics chapter is composed of five sections, section one addresses genes, section two addresses chromosomes, section three addresses meiosis, section four addresses inheritance and section five addresses genetic modification and biotechnology. Sections one through three mainly address concepts that can be categorized as microscopic entities and processes, section four discusses inheritance which is an interaction between the microscopic entities discussed in the first three sections and how they result in a particular trait, a macroscopic aspect. The fifth section discusses the application of the concepts studied in the first four sections in modern technology.

The students were assigned a project at the end of the fourth section and before the start of the firth section. The purpose of this project was to make sure the students have a solid foundation in the concepts discussed in the four sections. In summary, the project required the students to look at the genetic material of two parents (the full set of chromosomes and genes carried with the particular alleles), use this genetic material to decipher the resulting phenotype of each parent. Then the students were asked to use the chromosomes for each parent to represent a meiotic process and use the results of the meiotic process to show how an offspring would result from a combination of a sex cell from each parent. Then the students were required to use the chromosome combination of the offspring

to decipher the phenotype of the offspring (project assignment is on **Appendix 13**). The purpose of the project was to link the microscopic entities (genes and chromosomes) and processes (meiosis) and link them to the macroscopic result (phenotype) whilst putting all these concepts in context of one another, including the different symbols used (the alleles on the chromosomes). This should aid in the understanding of the upcoming section as it deals with applications of these concepts through manipulating genetics. Student questions regarding the project along with the project submissions were used as a data source. This will be discussed further in the upcoming section.

Sample Lesson (Appendix 2). In this section, one of the lessons is explained to demonstrate how the instruction implemented the study's objective. Each lesson is designated for one class period which lasts around 50 minutes.

At the end of section one in the genetics chapter (chapter 3), the IB requires the students to study sickle cell anemia as an example of how a gene mutation can have an observable effect on the individual. This sub-topic can be taught in a manner that supports the "multiple representation-type instruction" since sickle cell anemia is caused by a microscopic phenomenon (gene mutation), which influences consecutive cellular processes involving this gene leading to protein synthesis (another microscopic phenomenon) which consequently influences cell-shape and eventually influences the organism's physiology as a whole.

For this study, the aim for this lesson was for students to understand sickle cell anemia as a genetic disease that is a result of a DNA mutation, understand the micro, the macro and the symbolic aspects of learning about this disease and to link the microscopic/subcellular phenomena which is the DNA mutation to the macroscopic effects of sickle cell anemia, whilst having an understanding what happens between those two levels that lead to them. The lesson focused on applying the required IB objectives, in the context of multi-representational instruction. The lesson objectives given in the IB syllabus (**Appendix 1**) was structured in a

manner that coincides with an adaptation of Johnstone's triangle. The lesson started by introducing students to the macroscopic component through listing the symptoms of the disease (the outcomes of the mutation). The microscopic aspect of the disease was the process of DNA mutation that leads to this condition, and how this mutation in the DNA leads to the physical symptoms we see in individual with sickle cell anemia. The symbolic aspect was the different diagrams of the molecular entities and processes involved, which included the alleles that represented the gene for the disease, the DNA bases coding the gene represented by the base letter, and simplifications of the transcription and translation process.

The triangle in **Figure 3.1.** shows the three different representations denoted as the corners of the triangle vertices A, B and C whilst labeling the sides connecting the vertices labeled as D, E and F. Labeling the sides emphasizes the importance of not only addressing the different representations, but also the significance of constructing an explicit link between the different representations**.**

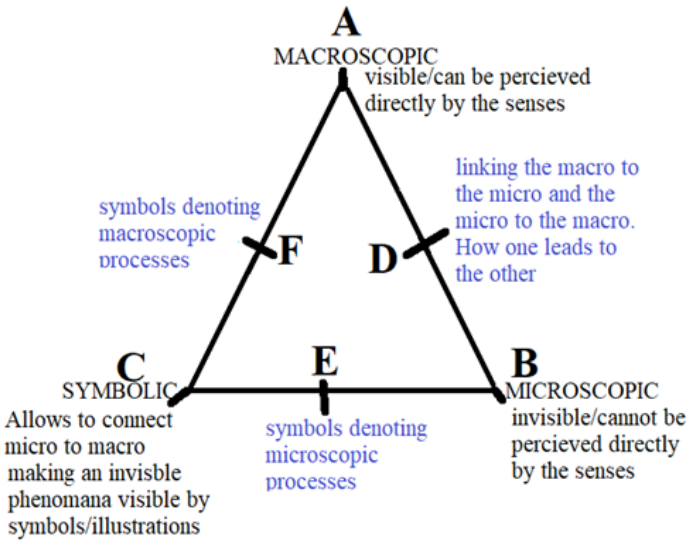


Figure 3.1. The breakdown of the triangle adapted from *Johnstone et al*.

In this lesson, students were first given a profile of an individual with an unknown genetic disorder and were given five minutes to come up with a list of questions and potential

checkups to investigate this patient's case. The patient's profile described physical symptoms of frequent troubled breathing, often felt extremely weak and had to stay at home, pale color. His/her profile also included information on relatives showing similar symptoms indicating the possibility of those symptoms being linked to a genetic disease. The answers were discussed in class and a list of predictions and check-up recommendations were compiled on the board. With the guidance of the teacher, the students also recommended that the patient gets a blood check. After discussing different predictions with the class, the teacher then proceeded to show a microscopic picture of the patient's red blood cells, and then compared it to an image of healthy red blood cells. The teacher then asked the students to compare and contrast the two images and come up with predictions regarding the effect of the misshaped red blood cells of the patient and possible links to the stated symptoms.

The teacher then asked the students to draw a macro/micro/ and symbolic triangle on their notebooks and annotate the diagram starting with the macro corner in what they understand is happening at the organismal/macro scale of the disease and micro in regard to what is happening at the cellular levels. The purpose of drawing the triangle is to allow the students to begin to link the macro to the micro.

Afterwards, the teacher prompted a discussion on the nature of genetic diseases, and what it means for a disease to be hereditary. This discussion served as a review of the content the students have learned before since genetic diseases have briefly been discussed in tenth grade. The teacher reminded the students that genetic diseases are diseases caused by errors in the genetic code and that such diseases, because they are in the DNA, could be passed down to the offspring. The students were then shown a video of a single base substitution mutation in the DNA and the teacher commented how a similar process occurring in a particular gene in the DNA that codes for Hemoglobin that causes the patient's symptoms. The teacher then explicitly

characterized the video as a symbolic representation of the mutation process that eventually leads to the sickle cell and asked the students to update the triangle structure accordingly.

A discussion was then initiated on different processes that involve DNA, such processes must include DNA replication where the DNA is copied prior to cellular division, transcription and translation where the DNA code is transcribed to RNA and this RNA is translated into amino acid chain forming a protein. The teacher then asked the students on the effect of a nucleotide substitution on those three processes, particularly how changes in DNA can be inherited and how changes in the DNA in particular areas that code for proteins can lead to the formation of a "faulty protein". The teacher compared the properties of the amino acid coded by the non-mutant base sequence to the amino acid coded by the mutant one and then showed a 3-D animated model of the protein translated from the non-mutated sequence and the mutated sequence.

The teacher urged students to annotate the diagram with what they understood was happening at the cellular and sub-cellular levels, which were categorized as micro levels, and what symbols were used to explain these processes. Students were then asked to annotate the diagram with what they perceived "symbolic" column with representations used to represent the cellular and sub-cellular process. After that, the teacher started a class discussion to explain how the cellular processes involved in mutation eventually lead to the physical symptoms of the patients using what the students know about how the red blood cell looks like, the role of the red blood cell in transporting oxygen, and the role of oxygen in the body.

At the end the lesson, the required content was explicitly summarized for the students within these vertices and sides of the triangle so that they are aware of where each concept fits within the micro/macro and symbolic triangle scheme. **Figure 3.2.** illustrates how a lesson (Full lesson plan in **Appendix 2**) on sickle cell anemia can be organized within this structure.

The students were asked to annotate the illustrations in their notes similarly throughout the class discussion to end up with a similar figure.

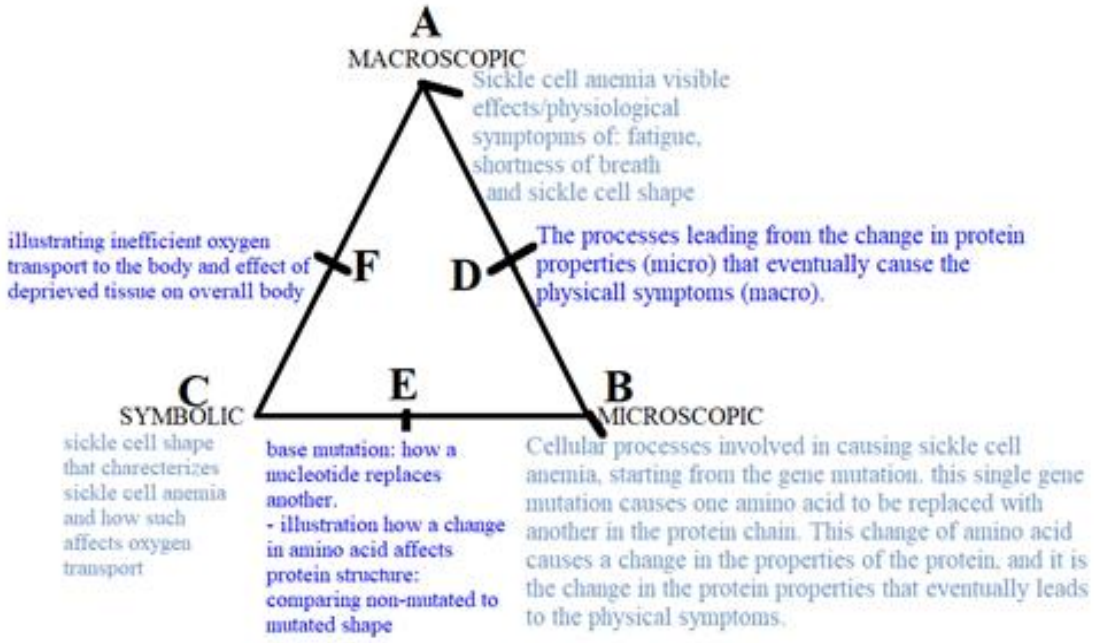


Figure 3.2. The concept of sickle cell anemia and the different elements of this disease organized within the multi-representational triangle.

To address the ontological dimension of the concepts, after the students completed their "triangle", they were guided to find terms discussed in the lesson on the supplementary unit sheet and fill it accordingly.

Student Resources. Since this study deals with implementing an instructional approach with which the students are not familiar, the teacher provided resources that served as a means to help transition the students into the new instructional approach whilst being

introduced to new material and guide them through the instructional objectives. Student resources were divided into two categories, note summaries and guided worksheets.

Note Summaries. Note summaries included summaries of DNA related content and processes that are prerequisites for the genetics unit content. these were used so that the student could use the content presented in the classroom in the desired context of the multiple representation instruction without being overwhelmed with the requirements of the new approach. For example, when discussing how a gene influences a particular trait and a student is asked to incorporate concepts from that lesson within the macro/micro/symbolic triangle, the related processes, transcription and translation, are visually available for the student on the resource sheet so that the student can categorize the concepts with more ease. This was particularly important when the students first began applying the macro/micro/symbolic levels to the taught content. The resource sheet included several visuals that relate to DNA:

1. Visual representation of how DNA is organized with protein into chromosome in an animal cell **(sample** in **Appendix 4)**
2. Cell cycle
    a. Interphase
        i. G1 phase
        ii. S-phase: DNA Replication
        iii. G2
    b. M phase
        i. Mitosis/meiosis
        ii. Cytokinesis
3. A key of symbols to use when denoting alleles (for sex-linked traits/ Mendelian genetics/ incomplete dominance/…)

4. Molecular Processes

   a. Transcription

   b. Translation

Guided Worksheets. Furthermore, the students were also given guided worksheets throughout the study. These worksheets can be categorized into two groups: an elaborate table with a list of all the concepts that were covered throughout the unit, referred to as the a "Supplementary unit sheet" and triangle templates **(**sample on **Appendix 6)** that the student filled out for different concepts as part of formative work in the class-room**.**

The purpose of the supplementary sheet was to encourage the students to categorize different concepts taught within the multiple representation scope whilst addressing ontological aspects. The supplementary unit sheet was divided into five parts, one part for each section in the chapter **(**sample of 3.1 supplementary sheet in **Appendix 5)**. The students were assigned to fill these sheets before the start of each section, and were given grades for completion, then the students were allowed to edit the sheet as the section material was taught. At the end of the section the sheets were graded based on accuracy and effort.

The supplementary sheet addressed each term as denoted in **Table 1** and required students to categorize the terms into multiple representation categories whilst answering ontology related questions, such as, "Is it something that physically exists?" and asking the students to sketch the concept. This sheet was meant to prompt students and prepare them to construct the multiple representation triangle and addresses the ontological aspect of the concept at a shallow level that is convenient for students first encountering these aspects

As for the triangle template, its purpose was to familiarize the students with identifying the multiple representations for the different concepts or phenomena taught that day. Triangle templates would be given out when explaining a new concept, and it would be

filled out throughout the class with the guidance of the teacher and the class discussion. These sheets served as a guided activity of how to categorize concepts.

Table 3.1

Supplementary Unit Sheet Given at The Beginning of the Unit and Filled Throughout the Instruction

Term/ concept	IB Definition	Is it macro/ micro/ symbolic	Why?	Is it something that physically exists?	Sketch	Does it encompass or relate to other concepts on this list? How?
i.e. chromosome						

Data Collection Instruments

Several instruments were used to collect data throughout the study to identify student misconceptions and how these conceptions change throughout the study. Data collecting instruments used in this study included: The Genetic Literacy Assessment Instrument (GLAI), two-tier questionnaire, semi-structured interviews, and Extended Response Questions (ERQs). The instruments were used to identify student conceptions before and throughout the study, and hence used to identify how the conceptions evolved throughout the duration of the study. These instruments were analyzed in a systematic manner to address the research questions. There were also other instruments such as transcribed videotaped class lessons, teacher journal and student work. These instruments were used to give further insight regarding the development of student conceptions. Unlike the aforementioned instrumented, these instruments were not analyzed systematically, instead, they were analyzed by extracting particular parts that addressed the research questions. The manner in which these instruments were analyzed is described in the upcoming section.

As mentioned in the reliability section, the GLAI and two-tier questionnaire had their own analysis method from the studies there were adopted from, however, the SSI's ad the ERQs were analyzed with the aid of an experienced colleague. These instruments are described in this section.

Genetics Literacy Assessment Instrument (GLAI)

Bowling, Acra, Wang, Myers, Markle, Dean and Moskalik (2007) developed a "Genetic Literacy Concept Inventory" (GLCI) that was intended to measure the level of genetic literacy of undergraduates in introductory biology and genetics courses" (Moskalik, 2007, p. 12). The GLCI was later referred to as the Genetics Literacy Assessment Instrument (GLAI) in the published paper (Bowling *et al*., 2008) and will hereafter be referred to as The GLAI in this study (sample questions from the GLAI are presented in **Appendix 7**).

Evaluation of the GLAI indicated that "it is a reasonable instrument for measuring genetics literacy of students before and after an introductory biology or genetics course" (Bowling et al., 2008, pp. 21).

The GLAI is a 30-item multiple choice questionnaire that has been used to measure genetic literacy for non-biology major undergraduates. Considering the IB is a university preparatory course, this allows for using the GLAI as a pre- and post-test in this study as an indicator for genetics understanding. The GLAI questions address six main topics in genetics, nature of the genetic material, transmission, gene expression, gene regulation, evolution and genetics & society. Under each topic, there are several sub-topics, and each of the 30 questions addresses one of the sub-topics (outlined in **Appendix 8**). This allows for the conceptions addressed per question to be identified. Hence, the GLAI is used as a tool to identify the concept or sub concept that the with which the student is challenged.

The validity and reliability of the instrument have been calculated, with a reliability estimate of 0.995 (N=395) for the pre-course and 0.997 (N= 330) for the post-course. This deems the instrument a "valid and reliable instrument for assessing the genetics literacy of undergraduate students" (p. 15). The GLAI was administered before, mid-way and at the end of the study. The students did not get feedback regarding this test until after they completed it as a post-test. How the GLAI is analyzed is outlined in the next section.

Two-Tier Questionnaire

The two-tier questionnaire is made up of several items (questions) and each item is composed of two parts (tier). The first tier of the item is a multiple-choice question where the choices given include a correct answer that reflects the desired level of understanding. Part two of each item asks the student to choose the best statement that justifies why they chose a particular answer for part one. The two-tier questionnaire used in this study has been adopted from Tsui and Treagust (2009). The two-tier questionnaire is reliable in uncovering students

understanding or misconceptions of genetics in terms of their scientific reasoning along both the domain-general and domain-specific dimensions (p. 1091). Seven items of this questionnaire were used as a pre- and post-test in this study (the seven items are listed in **Appendix 9**). These seven items are the ones that were made publicly available in published research. The two-tier items used each address one of six different "levels" of reasoning. These levels, adapted from Tsui and Treagust, are listed in **Appendix 10**. This allowed for the identification of different levels of thinking based on student performance on each item. The two-tier questionnaire is a "reliable instrument for diagnosing students' understanding in terms of reasoning in the domain of genetics" (Tsui and Treagust, 2009 , p.1081) as it has a Cronbach's alpha reliability ranging between 0.75 and 0.64" (p. 1073).

Prior to the beginning of instruction, this test was used to evaluate the students' existing conceptions of genetics through identifying their "reasoning level". After the instructional procedure, the students took the same seven-question two-tier questionnaire. Similar to the GLAI, the students did not get feedback regarding this test until after they completed it as a post-test. How the two-tier questionnaire is analyzed is outlined in the next section.

Semi-structured Interviews

Five students were selected randomly to be interviewed before, during (weekly) and after the study, totaling four interviews. Ideally, of the five students, there would have been two or three who have taken the honor's grade 10 biology and hence have been more prepared to the first year of IB biology, and the remaining would have been in a regular grade 10 class and have not been directly prepared to take IB biology (five students total). However, the choices of interviewees were limited by those who volunteered to participate in the study. As a result, the sample was divided into 4 previously honor students and one

regular students. This is considered when discussing the data analysis in the upcoming chapter.

The purpose of the interviews was to obtain an in-depth understanding of the change in understanding the genetics concepts targeted in this study. The interviews allowed the researcher to follow the learning journey of particular students more closely. The interviews were semi-structured and were used to explore the students' understanding of particular genetics concepts and track changes in this understanding as a result of the modified instructions. The interviews included questions related to the content covered throughout the lessons along with questions on the student input on the instruction. This was to give the researcher feedback on how they were reflecting on their learning.

As mentioned under the considerations section, the questions were reviewed by an experienced colleague teacher to identify the targeted conceptions in each interview question. Responses were analyzed for genetic related conceptions and the accuracy of those conceptions. The interviews were recorded and transcribed for the analysis. The average length of the interviews varied from one student to another. Sample interview questions are presented in **Appendix 11**.

Extended Response Questions

Throughout the instructional period of the study, the students completed weekly Extended Response Questions (ERQs) that aimed to track the process of learning occurring during that time. Each student completed four ERQs. As mentioned under the considerations section, the questions were reviewed by an experienced colleague teacher to identify the targeted conceptions in each question. The students have been taking their core and elective subjects in English (science, math, social sciences etc.) since kindergarten and hence can complete extended-response tasks on the topic without facing problems with the language. Therefore, through an extended-response question, students can share their understandings

without being limited with certain “choices” (such as in close-ended questions like multiple choice questions and true/false questions). An open-ended assessment can give insight regarding the students’ understanding, what conceptions they hold and their reasoning of that conception.

Videotaped Class Lessons, Student Work and Teacher Journal

Along with the aforementioned instruments, there were also transcribed class lessons, student work and teacher journal that served to give further insight regarding the teaching and the learning process. These were not analyzed in a systematic manner similar to the aforementioned instruments but were used as a source to gain further insight.

The video-taped lessons ensured that the classroom interactions between the teacher and students and amongst the students themselves was captured in a manner that can be referred to when checking for understanding. It was so that the details of the instructional implementation are known and can be accessed when evaluating its effectiveness. The content of these videotapes was transcribed to provide insight regarding details that might not have been considered yet might provide further insight. Furthermore, student work, mainly from the project discussed in previous section, were discussed in regard to how it reflected the learning process and the student understanding. Submissions of supplementary sheets (discussed earlier) were also considered. Sample student work is presented in **Appendix 15 (A, B and C)**.

Another source of data was the teacher reflective journal mentioned earlier under considerations section. The reflective journal was a way for the researcher to communicate input as a teacher on applying the instruction, report on student feedback in the class and other specific incidents that occurred during class provided further insight. This Journal is presented in the appendices (**Appendix 14**).

Data Analysis

As mentioned in the previous section, the data collecting instruments used in this study included: The Genetic Literacy Assessment Instrument (GLAI), two-tier questionnaire, semi-structured interviews, and Extended Response Questions (ERQs). Transcribed videotaped class lessons, student work and the teacher journal were used as instruments to provide further insight. Of the aforementioned instruments, the Genetic Literacy Assessment Instrument (GLAI), two-tier questionnaire, semi-structured interviews and Extended Response Questions (ERQs) were analyzed in a systematic manner to address the research questions. The remaining instruments, which were transcribed videotaped class lessons, teacher journal and student work were analyzed by extracting particular parts that addressed the research questions.

The first question, relating to student misconceptions prior to the study, was answered by analyzing the pre-test tasks (the GLAI and two-tier questionnaire) and the interview and ERQ conducted before the start of the instruction. The GLAI and two-tier questionnaire provided information regarding the students' genetics conceptions, while the interviews provided more in-depth information regarding these conceptions.

The second question pertaining to how the students' understanding changed over the course of the instruction was answered by looking at data provided by results collected from the consecutive administered GLAIs and two-tier questionnaire, the weekly interviews and extended response questions. This data provided information on the conceptions of students throughout the study from the beginning till the end and were used to compare the conceptions throughout the study to identify any change in conceptions that might have occurred. Further insight on this conceptual change was provided by videotaped class lessons, student work and teacher journal.

Genetics Literacy Assessment Instrument (GLAI)

As mentioned in the previous section, the GLAI is a thirty-item multiple choice test aimed at identifying students' genetic literacy by targeting, "*The 17 genetics sub concepts important for genetics literacy*". The sub-concepts and corresponding item from the test are presented in **Appendix 8**. These sub concepts are encompassed within six main topics, the nature of genetic material, transmission, gene expression, gene regulation, evolution and genetics and society.

The test's purpose is to be used, "in introductory level biology and genetics courses for nonbiology majors…[and] as a standardized measure across instructors, courses, and institutions in coordination with efforts to improve the teaching of genetics" (Bowling, *et al.*, 2008, p. 21). The test has content and discriminant validity, also, regarding reliability, as mentioned in chapter three, the GLAI has high stability and internal reliability values. The concepts and sub concepts identified per item were used to identify areas of misconceptions of the students. In addition to the listed sub-concepts per item, the options per multiple choice question provided further guidance regarding the nature of students' misconceptions.

To demonstrate how the misconceptions were identified, an example of item one from the GLAI (figure 3.3) is shown with the corresponding analysis. To identify student misconceptions, the topic and sub-topic were first identified (using the categories from **Appendix 8**) to identify the area of the misconception. In this case, the corresponding sub-concept identified according to Bowling *et al* (2008) for item one was under topic I, "The Nature of the Genetic Material", sub-concept c, "Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes".

1. What is the relationship among genes, DNA, and chromosomes?
a. Genes are composed of DNA and lie within chromosomes.
b. Genes are separate entities from either DNA or chromosomes.
c. Genes are found only in chromosomes and not DNA.
d. Genes are found only in DNA and not chromosomes.
e. Genes are composed of chromosomes and lie within DNA.

Figure 3.3 Item 1 on the GLAI test.

After identifying the sub-concept corresponding to the item, the options under each item were examined to specify the misconception. The correct answer for the item, "What is the relationship among genes, DNA, and chromosomes?" is option "a", "Genes are composed of DNA and lie within chromosomes" as highlighted on the figure. The remaining incorrect options give insight regarding the misconception held by the student on the nature of genetics. If the student chooses option "b", "Genes are separate entities from either DNA or chromosomes", this indicates that the student does not understand the relationship between the term genes, as units of information that are made up of DNA (structurally) and divided into chromosomes – which are super-coiled strands of DNA that carry genes on them. If the student chooses option "c", "Genes are found only in chromosomes and not DNA" this indicates that the student might understand that chromosomes carry genes but fails to understand that genes and chromosomes are both structurally made up of DNA nucleotides. If the student chooses option "d", "Genes are found only in DNA and not chromosomes" this indicates that the student might not understand the meaning of the term chromosome and how it links to the terms gene and DNA, specifically this might indicate that the student does not understand that chromosomes that carry genes. If the student chooses option "e", "Genes are composed of chromosomes and lie within DNA" this indicates that the student might not understand the difference between chromosomes and DNA regarding genes and have confused the two terms. A similar process was followed for all the items on the GLAI to

identify conceptions addressed and misconceptions identified. The results are shown in the **Table 3.2**.

Furthermore, the responses were analyzed for links to Macro/Micro/Symbolic and ontological aspects. The questions and the links they target are also shown in **Table 3.2**. To identify students' misconceptions and hence address the first research question, the first GLAI test is analyzed. Then to answer the second question regarding how these conceptions changed, the results of the first, second and third tests were compared and analyzed.

Table 3.2

Genetics Misconceptions Identified in the GLA Test and Study Related Aspect

Question		Related concept (in accordance with concepts set by Bowling *et al*., 2008)	Misconception(s)		Justification	Study Related Aspect (links to Macro/Micro/Symbolic and Ontological aspects)
1.	What is the relationship among genes, DNA, and chromosomes?	**Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.**	1. 2. 3. 4.	There is no relationship between genes, chromosomes and DNA There is only a relationship between genes and chromosomes but not DNA There is only a relationship between genes and DNA but not chromosomes Genes are composed of chromosomes	Failure to identify that chromosomes and genes are both structurally made up of DNA units; specifically, that chromosomes are condensed DNA strands that hold the genes within them.	5. Microscopic 6. Ontology of the terms in regard to how they relate
2.	Adult height in humans is partially determined by our genes. When environmental conditions are held constant, humans have a wide variety of heights (not just short, medium, and tall). Height is probably influenced by:	**IIIc. Most human traits, including diseases, result from the products of multiple genes interacting with environmental variables: examples include height, heart disease, cancer, and bipolar disorder.**	7.	Adult height, which is a trait with varying outcomes, is controlled by a single gene and/or is represented by 2 alleles	Identifying that traits with a wide variety of outcomes are often linked to the interaction of more than one gene. Dominance or lack of, is not considered, neither the fact of whether the genes are maternal or paternal.	-relating macroscopic (height) to micro (gene)
3.	Our understanding of how genes function indicates that:	**IIIa. Many genes code for proteins, which in turn produce individual traits.**	8. 9.	Gene products could be carbohydrates and fats Species use different mechanisms to express genes	The misconception that genes directly result in the formation of the trait rather than understanding that genes code for proteins and those proteins along with other mediating molecules and processes ultimately cause the trait to show. This mechanism is shared across different organisms. There is also the misconception that genes work individually and do not interact.	-microscopic (gene) - ontology of gene (function) - ontology of the gene
4.	What is the most likely way the genetic system (genetic material and the genetic code) of living organisms evolved?	**Ia. DNA is the genetic material of virtually all different types of organisms.**	10.	The same genetic system repeatedly developed at different times in various organisms.	Failure to understand the nature of evolution and how mutations accumulate over time to cause change	14. Linking micro (genetic code) to macro (evolution/ differences between species)

			11.	One genetic system developed early in the evolution of life in all organisms and remained.		15.	Ontology of genetic code
			12.	One genetic system developed but well after numerous different species existed.			
			13.	Different genetic systems evolved in different species.			
5.	Which of the following is INCORRECT regarding meiosis?	**IIa. Chromosome number is reduced by half during meiosis, which results in the formation of genetically different gametes.**	16.	Meiosis happens in both sexual and asexually reproducing organisms	Failure to understand that it happens only in cells that will form the gametes, and hence only in sexual organisms, and that is a process that halves the chromosome number to keep the number constant from generation to generation.	21.	Micro (meiosis)
						22.	Link micro (meiosis) to micro (cell)
			17.	Meiosis maintains the chromosome number after the division in sex cells		23.	Link micro (meiosis) to macro (organism)
						24.	Ontology of meiosis
			18.	Meiosis changes the number of chromosomes across generations			
			19.	Produces (genetically) identical cells			
			20.	Can happen to any cell in the body			
6.	Sometimes a trait seems to disappear in a family and then reappear in later generations. If neither parent has the trait, but some of the offspring do, what would you conclude about the inheritance of the trait?	**IIb. Understanding Mendelian patterns of inheritance, and their biological basis, allows probability statements about the occurrence of traits in offspring**	25.	A parent passes down two copies of a particular gene	Failure to identify that in order to express a recessive trait the individual must have the 2 recessive alleles and hence inherit the recessive alleles from BOTH parents, since the offspring inherits ONE copy from each parent.	28.	Link micro (gene) to macro (organism)
						29.	Ontology of a gene
			26.	If an individual has a trait and it is dominant it does not show			
			27.	For a recessive trait to be passed down to the offspring, it is enough that one parent has one or two copies of the gene.			
7.	An individual is found to have a mutation in a gene associated with breast cancer. In which cells is this form of the gene located?	**Id. virtually all cells within an individual contain the same genetic constitution- Different cells and tissues are produced through differential gene activity.**	30.	Mutations affecting a particular organ only happen in the cells/tissues of that organ	Failing to understand that for a mutation to be relevant, or have an effect, it should be in the DNA of all cells, not one. Meaning it must have been inherited from the parents (present in the gamete contributing to fertilization). Furthermore, a mutation that affects a particular	32.	Link micro (mutation) to micro (cells)
						33.	Link micro (mutation) to macro (organism)

			31.	Mutations that affect a particular gender can only exist in cells of that gender	organ/tissue is present in all cells of the body, not just that organ or tissue.		
8.	Mutations in DNA occur in the genomes of most organisms, including humans. What is the most important result of these mutations?	**Ib. Occasional errors in DNA structure and replication result in genetic variation.**	34.	Mutations produce new genes/ chromosomes /enzymes /cells for the organism	Failure to identify mutations as the main source of genetic variation within generations, and that mutations may or may not cause the formation of a new trait depending on the type of mutation (mutations may give rise to a new form a of a gene but do not create new genes, enzymes or cells)	35. 36.	Link micro (mutation) to micro (gene/ enzyme/ chromosome/ cells) Link micro (mutation) to macro (organism)
9.	Multiple genes are associated with complex diseases such as cancer and mental disorders. When an individual is tested for these genes, what do the results indicate?	**IVb. There are other genetic variations that result in disease less consistently, for example, the BRCA1 mutation associated with breast cancer.**	37. 38.	Having a certain gene means you will have the trait/outcome Having a certain gene means you will already have the trait/outcome	Failing to understand that even though genes code for traits, these traits are not necessarily actualized fully due to other influential factors such as the environment. Genes can be associated with traits or outcomes, but they do not necessarily lead to them or equate to those symptoms.	Link micro (genes) to macro (disorder)	
10.	Which of the following is a current benefit of the application of genetics and genetic technology to health care?	**VIa. The current and future application of genetics and genetic technology to such areas as health care, forensic analysis, genetically modified organisms, etc. holds great potential for improving life.**	39.	Genetic technology directly relates to finding cures for genetic diseases rather than detect them	Failure to identify the direct benefit of genetic technology, which is genetic screening for diseases or anomalies, and finding cures for diseases is a secondary product of these technologies (not a direct one).	Link micro (genes/genetic code) to macro (organism/society)	
11.	A woman has been told she carries a mutation associated with breast cancer. How does this influence her likelihood of developing breast cancer?	**IVb. There are other genetic variations that result in disease less consistently, for example, the BRCA1 mutation associated with breast cancer.**	40. 41. 42.	Having a gene associated with breast cancer means the individual will most likely NOT get the disease Having a gene associated with breast cancer means the individual will definitely get the disease Having a gene associated with breast cancer means the individual already has the disease	Similar to item 10, presence of a gene increases the likelihood of a trait to be expressed but it does not mean it will definitely be actualized	43.	Link micro (mutation) to macro (organism)

12.	Many geneticists study the genetic material of organisms such as mice, fruit flies, and yeast. They are able to apply what they learn from these organisms to humans because virtually all different types of organisms:	**Ia. DNA is the genetic material of virtually all different types of organisms.**	44. 45.	To study and apply study results across different organisms they should have the same amount of genetic material Having DNA as the structural component is enough to draw comparisons and apply results across different organisms	Failure to identify than the DNA is what the genetic code amongst organisms is made up of, and this code is universal in the sense that codons are translated to the same amino acids across different organisms, allowing knowledge about the genetic material to be transferred across species.	46. 47.	Link micro (genetic code) to macro (organism) Ontology of genetic code
13.	As HIV has spread around the world, we know some individuals are resistant to the effects of the virus even though they are HIV positive. Why?	**Va. Genetic variation is the rule rather than the exception in the living world and is the basis for evolution by natural selection: without genetic variation there can be no differential selection, and no survival of any species.**	48.	Genetic changes that provide resistance are produced in response to infection by the virus.	Failure to understand that evolution and natural selection are due to mutations that are favored by chance because they are adaptive to a given environment rather than mutations being produced in response to the environment itself. In this case, people who have resistance happen to have it by chance, and this chance is increased because it is favorable in this case. This contradicts the misconceptions that mutations for this resistance occur as a response to the disease.	49.	Link micro (genetic differences) to macro (organism/ resistance)
14.	Which of the following is a characteristic of mutations in DNA?	**Ib. Occasional errors in DNA structure and replication result in genetic variation.**	1. 2. 3. 4.	They are always beneficial They are always harmful They always have an effect/are expressed Occur at high rates	5. 6. 7.	Mutations are only passed on from parent to offspring if they occur in the sex cells Mutations occur in low frequency and tend to not be expressed (recessive) Mutations may cause variation among a population by creating new “versions” of a gene	8. 9. 10.	Micro (mutations) Ontology of mutations Link micro (mutation) to macro (organism)
15.	What is the relationship between DNA and chromosomes in higher organisms?	**Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.**	1. 2. 3. 4.	Chromosomes are found within DNA. There is no difference between DNA and chromosomes chromosomes produce DNA - DNA and chromosomes are completely separate structures.	The ontological understanding of DNA as a component that makes up chromosomes. Chromosomes organize the genes into separate structure of condensed DNA.	5. 6. 7.	Microscopic (DNA, chromosomes) Link micro (DNA, chromosomes) to macro (organisms) Ontology of genes in context of DNA and chromosomes

16.	Huntington's disease is a genetic disorder caused by a dominant gene. Symptoms begin in adulthood and the disease is ultimately fatal. What is an ethical dilemma presented by Huntington's disease when a parent is diagnosed with the disease?	**VIb. Like all technologies, genetic technologies are fallible and have unintended consequences, some of which can be harmful to individuals, families. or groups.**	8.	Ethical issues arise when an individual is tested for a particular genetic disease	Identifying ethical issues of genetic screening and predispositions of certain traits that could be fatal. When the parent is diagnosed with this disease, which is a dominant one, the ethical issue is testing the children as they are more likely to express the symptoms later on s it is a dominant disease.	9. Link Micro(genes) to macro (organism, society)
17.	Regarding complex traits such as IQ, lung cancer, prostate cancer, etc., how do geneticists describe the contributions of ones' genetic makeup and the environment?	**IIIc. Most human traits, including diseases, result from the products of multiple genes interacting with environmental variables: examples include height, heart disease, cancer, and bipolar disorder.**	- the environment plays the largest role in actualizing a trait - most traits are determined heavily by genetics with the environment having little effect on complex traits. d. The environment plays a major role in determining complex traits - Genetic differences among humans are so minor that essentially all variations observed among individuals are due to the environment in which they were reared.		Identifying the large role played by the environment in regard to actualizing certain genes into traits	10. Link micro (genes) to macro (trait, organism)
18.	How is the expression of genes regulated or controlled?	**IVc. Much of gene regulation involves turning genes on and off at the right time.**	- The expression of genes is not regulated or controlled. - Genes are turned on during development and stay on throughout one's life. - Genes are only turned on and off during development. - The expression of genes is only controlled by external factors.		Identifying that genes are turned on and off at variable times throughout one's life for varying outcomes such as cell function and differentiation	11. Ontology of genes
19.	If an individual has a genetic test for a mutation causing a particular disease, and the result is positive, what will that most likely mean?	**IVa. Some genetic variation results in disease in virtually every environment, for example, the mutations associated with Huntington disease, Tay-Sachs disease, and cystic fibrosis.**	- The individual will definitely exhibit the disease, regardless of whether it is due to a dominant or recessive mutation. - The individual will definitely exhibit the disease only if it is due to a dominant mutation.		Similar to items 10 and 13, understanding that possessing a certain gene increases the chance of a particular outcome but does not necessarily equate this outcome.	12. Link micro (mutation) to macro (organism) 13. Ontology of mutations

			- A positive test for the mutation indicates that the individual already has the disease. - The environment during the individual's development will be the primary determinant of whether the individual exhibits the disease.				
20.	What effect, if any, does an individual's environment have on the development of his or her traits?	**IIIb. The functions of a gene and its protein product can be affected by the environment at one or many steps involved in producing a given trait.**	- the environment has little or no effect on most traits in an individual. - It sets the potential for the development of most traits in an individual. - It is a dominant factor for determining most traits in an individual. - It does not have any effect on an individual's traits but can have an effect on the traits of an individual's offspring.		Similar to item 20, the role of the environment in actualizing the traits determined by the genes	14. 15. 16.	Link micro (gene) to macro (organism) Link macro (environment) to macro (organism) Link macro (environment) to micro (gene)
21.	Your muscle cells, nerve cells, and skin cells have different functions because each kind of cell:	**Id. virtually all cells within an individual contain the same genetic constitution- Different cells and tissues are produced through differential gene activity.**	- different types of cells carry different kinds and/or numbers of genes that determine their function. - function of a cell is determined by its location - different types of cells arise due to different mutations.		Similar to item 19, understanding that all cells have all the genetic material, however the different functions of the cells arise because different parts of the genetic material have been turned on/off.	17.	Link micro (gene) to micro (cells)
22.	At what times during an individual's life does the environment influence the expression of his or her genes?	**IIIb. The functions of a gene and its protein product can be affected by the environment at one or many steps involved in producing a given trait.**	18. 19. 20.	environment influence the expression of genes only after birth till adulthood environment influence the expression of genes only after birth till the rest of the individual's life environment has an effect of genes only during key stages of life	Understanding that the role of the environment starts from conception, and stays throughout the person's life, and that the influence of the environment depends on how drastic the environment is and at what stages is it acting.	22. 23.	Link macro (environment) to micro (gene) Link macro (environment) to macro (organism)

				such as puberty and menopause.		
			21.	Environment has little or no effect on how genes are expressed.		
23.	Which of the following is INCORRECT regarding the genetic differences among ethnic groups?	**Vb. Genetic variation is much greater within traditional human ethnic groups than among them. Superficial phenotypic differences do not reflect the high degree of genetic relatedness among traditional ethnic groups**	- The DNA sequence is substantially different among humans - Genetic differences responsible for skin color represent a substantial portion of the human genome. 1.		Identifying that genetic differences within an ethnic group are fewer than between ethnic groups.	2. Link micro (DNA sequence) to macro (organisms)
24.	What is the relationship between genes and traits expressed in individuals?	**IIIa. Many genes code for proteins, which in turn produce individual traits.**	3. 4. 5. 6.	Genes code for DNA Genes code for chromosomes Genes code for carbohydrates The environment rather than genes is primarily responsible for individual traits.	Understanding that genes, which are made up of DNA, code for proteins and that the proteins are then, through mediating processes responsible for actualizing the traits coded for by the genes	7. Link micro (genes) to macro (traits of an organism)
25.	Which of the following does NOT accurately reflect Charles Darwin's basic principles of evolution?	**Va. Genetic variation is the rule rather than the exception in the living world and is the basis for evolution by natural selection: without genetic variation there can be no differential selection, and no survival of any species.**	1. 2. 3.	The capacity of biological species to reproduce is limited. The capacity of the earth to sustain continuous population growth is unlimited. Individuals are equally equipped to survive changes in the environment.	Understanding that variation is the key to natural selection	4. Link micro (genetics) to macro (organisms)
26.	Which of the following is NOT considered an ethical or legal concern?	**VIc. Science often can tell us what we can or cannot do, but it does not always indicate clearly what we should do. Those decisions arise from the intersection of**	1. 2.	Allowing prenatal sex selection is not an ethical concern. There are no ethical or legal concerns regarding counseling couples not	Understanding outcomes of genetic technology between ethical issues surrounding genetic screening and determining fates of individuals and benefits such as preventative measures	6. Link micro (genetics) to macro (organisms/society)

		science with ethics, the law. and public policy.		to have abnormal babies that require costly care.		
			3.	There are no ethical or legal concerns regarding utilizing embryonic stem cells for research.		
			4.	There are no ethical or legal concerns regarding giving insurance companies the right to deny insurance to those individuals known to have a high risk or genetic disease.		
			5.	Offering mothers 35 years of age or older the opportunity to have prenatal diagnosis for chromosome anomalies is controversial.		
27.	Cystic fibrosis (CF) is a recessive disorder, meaning that an individual must have two copies of an abnormal CF gene to be affected. What is the probability that a child of two individuals who each have one copy of the abnormal gene will be affected with CF?	**IIb. Understanding Mendelian patterns of inheritance, and their biological basis, allows probability statements about the occurrence of traits in offspring.**	7.	For an individual to be affected by a recessive disease, it is enough to inherit one copy of the recessive allele from one parent	Using Punnett square to predict the possibility of an offspring receiving both recessive allele from parents.	8. Link micro (gene/mutation) to macro (trait/organism)
28.	Which of the following is a correct statement about science and the scientific method?	**VIc. Science often can tell us what we can or cannot do, but it does not always indicate clearly what we should do. Those decisions arise from the intersection of science with ethics, the law. and public policy.**	9.	science and the scientific method are rarely able to provide explanations of the natural world.	Identify the scientific method processes of inquiry which include repeatable observations and testable hypotheses and from this process we obtain the information we build on	-
			10.	science and the scientific method provide explanations that include the supernatural world.		
			11.	science and the scientific method are unlikely to contribute significantly to improving the human condition.		

			12.	conclusions reached by science and the scientific method are not open to question in the light of new data and observations.			
29.	The muscle cells of humans contain 46 chromosomes. How many chromosomes do unfertilized human egg cells contain?	**IIa. Chromosome number is reduced by half during meiosis, which results in the formation of genetically different gametes.**	13.	Body cells and sex cells carry the same number of chromosomes	Comparison between body cell and gamete in regard to chromosome number and understanding that gametes carry half the number of chromosomes (are haploid).	16.	Link micro (chromosome) to micro (sex cell)
			14.	Sex cells carry twice as many chromosomes as body cells			
			15.	Body cells carry four times more chromosomes than sex cells			
30.	What is an example of an unexpected consequence when current genetic technologies are used?	**VIb. Like all technologies, genetic technologies are fallible and have unintended consequences, some of which can be harmful to individuals, families. or groups.**	17.	Genetic technologies are very specific in regard to what is being screened	Differentiating between direct benefits and side outcomes of genetic technologies	18.	Link micro (genetics) to macro (organisms)

Two-Tier Questionnaire

The Two-Tier Questionnaire was administered twice throughout the study, once before the study and once after the study. During the first administration of the test, which was done in class, twenty-three students participated. During the second, which was done online at the end of the study, only fourteen students participated. Similar to the GLAI pre-test, all students participated in the pre-two-tier questionnaire and this test will be analyzed to identify student misconceptions and address the first research question.

The two-tier questionnaire, as the name suggest is made up of two questions (tiers) per item. The first question addresses content knowledge, and the second addresses the reasoning behind the choice of the first question's answer. The student does not get credit for the item unless both questions are answered correctly, hence, this method addresses the issue with answering multiple choice questions randomly and getting the answers correct (Tsui & Treagust, 2009). The two-tier questionnaire addresses several aspects that are encompassed in this study. Multiple levels that are represented in genetics are acknowledged. Tsui and Treagust (2009) suggest that,

> "the traits or phenotypes of an organism are at the macroscopic level, whereas cells, chromosomes, or DNA are at the microscopic and submicroscopic level, and genotypes are at the symbolic level... students' understanding of genetics depends on their ability to deal with these concepts and processes simultaneously at several levels of organization and to connect them as an interrelated whole" (p.1076)

Furthermore, the ontological aspect of concepts is also acknowledged as a source of student difficulty,

> "Another reason for students' learning difficulty is that they have to reason with concepts and processes that are at ontologically distinct levels. For example, genes or DNA molecules are informational but the traits they control are physical" (p.1076)

The two-tier questionnaire is meant to address six different "levels" of reasoning. These levels, adapted from Tsui and Treagust, are mapped in **Appendix 10.** These levels were developed based on several documented studies regarding student conceptions in genetics, and the two-tier questionnaire was created accordingly. The two-tier questionnaire is made up of 14 questions total, however, only 7 out of the 14 items were used due to reasons discussed in Chapter three. The seven items from the two-tier questionnaire address all six types of reasoning included and are described in **Table 3.3**. **Table 3.3** also shows the related study aspects (links to Macro/Micro/Symbolic and ontological aspects) addressed in each question. This is important when analyzing the student responses to detect the study related aspect that is challenging.

Table 3.3

Item Number on the Two-Tier Questionnaire and Corresponding Genetics Reasoning and Related Study Aspect.

Item Number	**Reasoning Type**		**Study related aspect**
1	I	Cause-to-effect reasoning; Mapping genotype to phenotype	Linking Symbolic to Macro
6	II	Cause-to-effect reasoning; Monohybrid inheritance: Mapping genotype to phenotype	Linking Symbolic/Micro to Macro
7	III	Effect-to-cause reasoning: Mapping phenotype to genotype	Linking Macro to Symbolic
2,5	IV	Effect-to-cause reasoning: Monohybrid inheritance: Mapping phenotype to genotype	Linking Macro to Micro/Symbolic
4	V	Process reasoning: Mapping information in DNA base sequence (genotype) to amino acid sequence in protein synthesis (phenotype)	Ontology of a gene
3	VI	Process reasoning: Punnett squares (input/output reasoning): Meiosis process (event reasoning) Mitosis process	Linking symbolic and Micro

To demonstrate how the misconceptions have been identified from the two-tier questionnaire, an example of item one from the two-tier questionnaire (figure 3.4) is shown with the analysis. To identify student misconceptions, the type of genetic reasoning is first identified (using the table from **Appendix 10**). Then the two tiers are examined, the first tier gives a general idea regarding possible student misconceptions. However, it is the second tier that provides a better insight regarding student misconceptions as it asks the students to show their reasoning. Hence, we do not only depend on the content knowledge show when answering the first tier. In this case, the corresponding genetic reasoning identified according to Tsui and Treagust (2009) for item one is type I, "Cause-to-effect reasoning; Mapping genotype to phenotype". This means that in this Tier, students are expected to link genotype [cause] whether it is heterozygous or homozygous, to expected phenotype [effect].

Tier 1
The trait, curly hair, is dominant to straight hair. If we use "C" to represent the dominant allele (gene) curly hair and "c" for the recessive allele, would a person with genotype Cc have curly hair?
[ ] 1. Yes
[ ] 2. No
[ ] 3. Don't know

Tier 2
Reason for the above:
[ ] 1. The person needs to have CC for curly hair.
[ ] 2. The dominant allele C is expressed in a Cc condition.
[ ] 3. The person may or may not have curly hair.
[ ] 4. The recessive allele c is expressed.

Figure 3.4. Item 1 on the Two-Tier questionnaire.

In Tier 1, students are supposed to answer with "Yes" regarding the expression of a dominant trait (curly hair) in the heterozygous form (Cc). Answering the first tier with "no" or "don't know" indicates that the student is facing difficulty with linking the genotype "Cc" with the outcome. This difficulty is clarified when examining the students' answer to the second tier. If the student chooses option one for the second tier, "The person needs to have

CC for curly hair," it indicates that the student does not understand that only one dominant allele is enough to express the trait (hence either the homozygous form, CC or the heterozygous one Cc will yield the same trait), and thinks that both alleles must be present to express the dominant trait. If the student chooses option two for the second tier, " The dominant allele C is expressed in a Cc condition," which is the correct option, it indicates that the student understands that only one dominant allele is enough to express the trait (hence either the homozygous form, CC or the heterozygous one Cc will yield the same trait). If the student chooses option three for the second tier, " The person may or may not have curly hair," it indicates that the student is struggling in linking a particular genotype to a phenotype, and it might also indicate that the student is facing difficulty deciphering the symbolism in the genotype. If the student chooses option four for the second tier, " The recessive allele c is expressed", it indicates that the student is struggling with the concept of what it means for an allele to be "dominant" or "recessive," and it might also indicate that the student is facing difficulty understanding how dominant and recessive alleles interact to express a particular trait.

This process was done for all the items on the test and the results are shown in the **Table 3.4.**

Table 3.4

Genetics Misconceptions Identified in the Two-Tier Questionnaire

Question	**Misconception held by the student**	**Justification**
Item 1, Tier 1: The trait, curly hair, is dominant to straight hair. If we use "C" to represent the dominant allele (gene) for curly hair and "c" for the recessive allele, would a person with genotype Cc have curly hair?	Heterozygous genotype (Cc) does not express the dominant trait Dominant trait is only expressed in homozygous form	3. Failure to recognize that dominant traits are expressed in both heterozygous and homozygous form symbolized by Cc and CC (genotype).
Item 1, Tier 2: Reason for the above [Item 1, Tier 1]?	4. The person needs to have CC for curly hair. 5. The person may or may not have curly hair. 6. The recessive allele c is expressed.	7. Failure to recognize that presence of one dominant allele, symbolized by "C" is enough to express the dominant trait
Item 2, Tier 1: Which of the following best describes the trait in the following pedigree?	8. A dominant allele can be present in the parents, not show, and be passed down to off-spring and show	9. Failure to map from phenotype to genotype between generations using a pedigree chart
Item 2, Tier 2: Reason for the above:	10. The trait is recessive Only one of the three children in the second generation has the trait. 11. The trait is dominant because both the female in the first generation and her son have the trait. 12. The trait can be either recessive or dominant based on the pedigree.	13. Failure to identify the male individual in the third generation having two recessive alleles in his genotype that must have come respectively from his two parents, who were heterozygous for the trait and thus did not show the trait.
Item 3, Tier 1: The following shows a "Black Box" that provides a simplified model to show a process in genetics. What does the "Black Box" represent?	14. The image shown to divide the cell into four cells with half the number of the original chromosome number represents fertilization 15. Represents a cell division that occurs after fertilization	16. Failure to identify the "black box" as an analogy representation of meiosis—the reduction cell division for producing haploid sperms or eggs.
Item 3, Tier 2: Reason for the above [Item 3, Tier 1]?	17. Different combinations of chromosomes are responsible for the different cells and function in the body	19. Students did not understand the processes of meiosis and fertilization and their roles in maintaining the constant diploid number of chromosomes in a species from generation to generation.

	18.	Cells divide to form different cells with varying chromosome number to fulfill different functions	
Item 4, Tier 1: Which one of the following is the best description of a gene?	20.	Genes are the smallest unit of structure in a chromosome.	Understanding genes as an instruction unit rather than structural, that codes for particular instructions/traits
	21.	Genes are a segment in a DNA molecule.	
Item 4, Tier 2: Reason for the above [Item 4, Tier 1]?	22.	Genes are defined in regard to the structural role they play in composing chromosomes	Genes are units of information in chromosomes rather than structural units, made up of DNA and code for proteins
	23.	Genes are defined as being structurally made up of DNA	
Item 5, Tier 1: The pedigree chart below shows the inheritance of a common genetic disease in Western Australia. Which of the following best describes the allele that gives rise to the trait?	24.	Disease is sex-linked dominant	Identifying different modes of inheritance (sex-linked vs autosomal) and failure to map from phenotype to genotype between generations using a pedigree chart whilst considering the gender (similar to item 3)
	25.	Disease is sex-linked recessive	
	26.	Disease is autosomal dominant	
Item 5, Tier 2: Reason for the above [Item 5, Tier 1]?	27.	If both a female and male are affected by a disease, then it must be autosomal	For a disease to be sex-linked, the males affected must inherit the disease from their mothers, and for the female to be affected, both parents must be carriers of the disease and hence the father must have it
	28.	If the parents are normal but one of the offspring is affected, then the disease is definitely autosomal recessive	
Item 6, Tier 1: Some dogs bark when following a scent, others are silent and are called silent trackers. Barking is dominant (allele B) to non-barking (allele b). A hunter owns a barker which he wants to use for breeding purposes. However, he wants to be sure it has a genotype of BB. What is the genotype of the bitch he should mate with this dog?	29.	To check whether an organism is heterozygous or homozygous dominant, crossing with another homozygous dominant will yield observable results	31. Understanding the interaction of dominant and recessive alleles and how alleles are passed down from parents to offspring. 32. Using phenotype of offspring to determine parental genotype
	30.	To check whether an organism is heterozygous or homozygous dominant, crossing with another heterozygous will yield observable results	
Item 6, Tier 2: Reason for the above [Item 6, Tier 1]?	1.	If no silent trackers appear in the offspring, he can be sure that his dog's genotype is BB.	Understanding that if recessive trait is expressed in offspring then offspring must have inherited it from both parents meaning both parents must be carriers or homozygous recessive.
	2.	- If the dog is Bb, the chances of getting silent trackers in the offspring are zero.	

Item 7, Tier 1: Peter is an albino who was born without the ability to make a pigment in the skin. Albinism is a recessive characteristic. Suppose we use “A” for the dominant gene (allele) and “a” for the recessive gene, what would be Peter’s genotypes (genes) for albinism?	3.	Recessive traits can be expressed in heterozygous form
Item 7, Tier 2: Reason for the above [Item 7, Tier 1]?	4.	Having one copy of recessive allele is enough to express recessive trait
	5.	In heterozygous form, the recessive allele is expressed

For a recessive trait to be expressed both alleles must be recessive.	
Having only one recessive allele is not enough to cause albinism	

Semi-structured Interviews

Five of the students were interviewed before, during (weekly) and after the study for an in-depth understanding of the change process. There was a total of four interview sets, and each set had a different number of questions. Interview questions were adopted and modified from a study by R. Duncan (2007) that used qualitative methods to analyze students' reasoning and problem solving in the domain of genetics. However, the method of analysis used in this study was different as the questions were modified to fit the content of the material taught and to include questions that allowed students to give their input on the instruction.

Conceptions addressed in each interview questions were identified with the aid of an experienced colleague to establish reliability. Conceptions developed by Bowling *et al.* (2008) were used as reference when identifying concepts addressed in each question. Then these concepts were elaborated to address the particular conception addressed by the questions. This process was meant to establish reliability and was elaborated under the reliability section of this chapter. Target conceptions for every question in all four sets of interviews and relevant Bowling *et al.* (2008) conceptions are outlined in **Table 3.5**. **Table 3.5** also shows how each question addressed the study aspects (links to Macro/Micro/Symbolic and ontological aspects).

Table 3.5

Targeted Genetics Conceptions Addressed in Interview Questions and Relevant Bowling et al. (2008) Conceptions

Interview set	Question	Relevant Bowling *et al.* (2008) Conceptions	Targeted Conception	Links to Macro/Micro/Symbolic and ontological aspects
1	define DNA.	Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.	DNA is a type of nucleic acid (macromolecule) that makes up the genetic material	6. DNA ontology
	define chromosomes.	Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.	7. Are made up of condensed DNA Carry genes	8. chromosome ontology
	define genes.	Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.	9. Made up of DNA 10. Code for proteins Act as instructions of the cell	11. gene ontology
	If you're given a super microscope and you're told to find a gene, where would you zoom in and how would you know if it is a gene or not	Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.	- what differentiates a gene from other DNA segments is the functional role of a gene in coding for proteins	- gene ontology
	Do all cells carry the same genes?	Id. virtually all cells within an individual contain the same genetic constitution- Different cells and tissues are produced through differential gene activity.	N/A	12. link micro (genes) to micro (cells)
	What is genetic material made up of?	Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.	-Structurally, the genetic material is made up of DNA - Genetic material is divided into chromosomes -different chromosomes carry different genes - genetic material is made up of genes and non-coding sequences	DNA and gene ontology
	How do we look like our parents, and how come we differ from our siblings?	IIb. Understanding Mendelian patterns of inheritance, and their biological basis, allows probability statements about the occurrence of traits in offspring.	- our genetic material is made up of 50% maternal and 50% paternal chromosomes - how much we look like either parent is determined by what genes were inherited from each parent, and the interaction of those inherited genes	- link micro (genes) to macro (individual)
	Put DNA, gene, and chromosome in a sentence.	Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.	-Structurally, the genetic material is made up of DNA - Genetic material is divided into chromosomes -different chromosomes carry different genes	- ontology of genes, DNA and chromosomes.

	How are genes expressed? [an example of a trait was given to ask the question]	IIIa. Many genes code for proteins, which in turn produce individual traits.	-		- linking micro (gene) to macro (trait) - ontology of gene	
2	Differentiate between chromosomes, sister chromatids, homologous chromosomes ad chromatin. What do they describe, and can DNA be two of those at the same time?	Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.	13. 14. 15. 16.	Sister chromatids are a result of when chromosomes are replicated before cell division Homologous chromosomes are chromosomes that carry the same genes and inherited from each parent. Chromatin is the uncondensed DNA that exists when the cell is not preparing to divide. During prophase 1 of meiosis sister chromatids and homologous chromosomes can be identified.	17.	Ontology of DNA and DNA related terms
	Differentiate between allele and gene, and how can you differentiate them on a DNA strand.	-	- alleles are different forms of a gene - alleles of the same gene differ in a few bases		- ontology of genes	
	How does a cell read a gene?	IIIa. Many genes code for proteins, which in turn produce individual traits.	-		- ontology of genes - linking micro (gene) to micro (cell)	
3	What is the difference between genotype and phenotype?	IIIa. Many genes code for proteins, which in turn produce individual traits.	18. 19.	Genotype is the allele combination carried by the individual's genes Phenotype is the product of this allele combination manifested through gene expression/protein synthesis	20.	Linking micro (genotype) to macro (phenotype)
	What is the difference between a chromosomal disorder and a genetic mutation? How do they compare in regard to modes of inheritance?	Ib. Occasional errors in DNA structure and replication result in genetic variation. IIa. Chromosome number is reduced by half during meiosis, which results in the formation of genetically different gametes. IIb. Understanding Mendelian patterns of inheritance, and their biological basis, allows probability statements about the occurrence of traits in offspring.	21. 22.	Chromosomal disorders arise due to failure of chromosomes to divide during the meiosis of either parents Genetic mutations/disorders are a result of the inheritance of a mutated gene from either parent	23. 24.	Ontology of chromosomal disorders Ontology of mutations

	how is the sex of the offspring determined?	-	- sex of the off-spring is determined by the inheritance of particular sex chromosomes from parents - this is random depending which gamete joins with which gamete resulting in what twenty-third chromosomal combination	- link micro (sex chromosomes, meiosis) to macro (sex of organism)
	Why do we look like our parents, what processes that happen microscopically, make us look like our parents?	IIa. Chromosome number is reduced by half during meiosis, which results in the formation of genetically different gametes. IIb. Understanding Mendelian patterns of inheritance, and their biological basis, allows probability statements about the occurrence of traits in offspring.	- our genetic material is made up of 50% maternal and 50% paternal chromosomes - how much we look like either parent is determined by what genes were inherited from each parent, and the interaction of those inherited genes	- link micro (genes) to macro (physical traits)
	Organize the concept of [down-syndrome/sex determination] within the triangle scheme	-	- microscopic: meiotic process resulting in chromosomes to fail to divide, resulting in zygote with uneven number of chromosomes - macroscopic: uneven number of chromosomes results in traits associated with down syndrome - symbolic: denoting the 23rd chromosomes and meiotic process	- linking micro, macro and symbolic

4	Define DNA.	Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.	DNA is a type of nucleic acid (macromolecule) that makes up the genetic material		25.	Ontology of DNA
	Define Chromosomes.	Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.	26. 27.	Are made up of condensed DNA Carry genes	28.	Ontology of Chromosomes
	Define genes.	Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.	29. 30. 31.	Made up of DNA Code for proteins Act as instructions of the cell	32.	Ontology of genes
	What is meant by the genetic code being universal?	Ia. DNA is the genetic material of virtually all different types of organisms.	Codons, a set of three nucleotides, codes for the same amino acid across different species.		33.	Ontology of genetic code
	How are traits expressed?	IIIa. Many genes code for proteins, which in turn produce individual traits.	-		- linking micro (genes) to macro (traits)	
	How are mutation passed inherited?	Ib. Occasional errors in DNA structure and replication result in genetic variation.	34.	Inheritance of a mutation is determined by what genes were inherited from each parent, and the interaction of those inherited genes	37.	Linking micro (meiosis and fertilization) to macro (organism)

35. The meiotic products from both parents combined should include the mutated genes
36. Probability of such could be deduced from a Punnett square

As for the analysis of the student responses, the student responses were compared to the identified conceptions (from **Table 3.5**) and misconceptions were identified. This process was also done with the aid of a colleague and the details of this process is outlined in the reliability section of this chapter. In summary, student responses were compared to the target conceptions, if student response fit the target conception description this would mean that the student holds the accurate conception, if not this means the student has a misconception of a particular nature, The nature of each misconception different from student to student and hence categories were made based on student responses. **Table 3.6** demonstrates how the response of one student (student 8) on the first interview was used to identify a list of misconceptions. When analyzing another student's interview responses, new misconceptions might be identified, or the student could hold a similar misconception to student 8. After all the misconceptions were identified from all the student responses, the frequency of these misconceptions was identified to determine any predominant misconceptions. The remaining interviews were analyzed in a similar manner and the conceptions of the students were identified and compared to address the research questions of the study. The micro/macro/symbolic/ontological aspects identified in **Table 3.5** were also used to categorize the area of difficulty that students were struggling with. Furthermore, the student responses were also used to identify "problem areas" in regard to the study aspect (micro/macro/symbolic and ontological) which aided in the categorization of misconceptions and challenges. This is discussed in chapter four when discussing the results.

Table 3.6

Misconceptions identified from Interview 1 with student 8

Question (with target conception below)	Student Answer	Identified Misconception	Identified Problem Area
1. Define DNA. DNA is a type of nucleic acid (macromolecule) that makes up the genetic material	"DNA is like Deoxyribonucleic acid which is basically like a recipe book for human beings like how they are made up of physical features and such"	2. DNA and gene are equivalent 3. DNA codes for traits	4. DNA ontology
5. Define chromosomes. Are made up of condensed DNA and carry genes	"Chromosomes are composed of DNA and are concentrated in constant shapes and are in DNA replications"	6. student defines chromosomes in context of DNA but not in context of genes	7. chromosome ontology
8. Define genes. Made up of DNA, Code for proteins, Act as instructions of the cell	"I don't know..."	9. student cannot define gene	10. gene ontology
11. If You're Given a "Super Microscope" and You're Told to Find a Gene, Where Would You "Zoom In" and How Would You Know if It Is A Gene or Not? what differentiates a gene from other DNA segments is the functional role of a gene in coding for proteins	**Student 8:** I zoom it at the nucleus in the cell, and just try to find the double helix, so I would figure it the DNA **Teacher:** So, if once you found the DNA you found the gene? **Student 8:** Not necessarily **Teacher:** Then how would you know if you found the gene or not? You're telling me you found a gene; how can you know if you found a gene or a DNA? **Student 8:** I don't really know the difference between a gene and a DNA	12. Student cannot differentiate between gene and DNA	13. gene ontology
14. Do All Cells Carry the Same Genes? Id. virtually all cells within an individual contain the same genetic constitution- Different cells and tissues are produced through differential gene activity. (Bowling *et al.* (2008))	**Student 8**: Yes, all cells have the same genes **Teacher**: Then how come there are different types of cells? **Student 8:** Certain chains are like they stand out more so certain job is done in the cell **Teacher**: How do they stand out? **Student 8:** That's… I don't know, I don't remember	15. Student identifies that all cells have the same genes but does not recognize why cells are differentiated	16. link micro (genes) to micro (cells)

17.	How Do We Look Like Our Parents? Why do we look different from our parents? - our genetic material is made up of 50% maternal and 50% paternal chromosomes - how much we look like either parent is determined by what genes were inherited from each parent, and the interaction of those inherited genes	**Student 8:** By having the same genes as them **Teacher**: So, we have the same genes as our parents? **Student 8**: Not the exact same, but very similar **Teacher**: So how come you and your siblings look different? **Student 8:** I look very similar to my siblings, but I don't really know why we look different **Teacher:** How would you think that would work? How would that happen? You and your siblings are like your parents but at the same time are different from your siblings? **Student 8:** She took more from my mommy's genes and I took more of like my father's **Teacher**: How would that happen? **Student 8:** From the ratios of how it's activated, the genes **Teacher:** Okay so you have both your mom's and dad's but depends which one's activated? **Student 8**: Depends of which one's you're made up of more	18. 19. 20.	Student fails to recognize systematic method of inheritance through meiosis Student thinks that females inherit more from their mom and ales more from their dad Student thinks we have similar genes to parents but does not clarify what is meant by that	21. 22.	link micro (genes) to macro (individual)
23.	Put DNA, gene, and chromosome in a sentence. -Structurally, the genetic material is made up of DNA - Genetic material is divided into chromosomes -different chromosomes carry different genes - genetic material is made up of genes and non-coding sequences	"They are all like recipe books, so that makes up the human being, they're all related to each other. The genes are in the DNA and chromosomes are made of DNA"	24.	Student does not differentiate between gene, chromosome and DNA	25.	DNA and gene ontology

Extended Response Questions

Throughout the study, the students completed weekly Extended Response Questions totaling four throughout the unit. Conceptions addressed in each question were identified with the aid of an experienced colleague to increase reliability. The process of analyzing the questions to identify what conceptions they targeted was described in detail in the reliability section of this chapter. Similar to the interview questions, conceptions developed by Bowling *et al.* (2008) were also used as reference when identifying concepts addressed in each question. These concepts were then elaborated and/or modified to address the ERQ question specifically. Conceptions targeted per question and relevant Bowling *et al.* (2008) conceptions are outlined in **Table 3.7**. Furthermore, relevant aspects (to the study: micro/macro/symbolic/ontological) of each question were identified in **Table 3.7**; these aspects aided in categorizing student misconceptions and provided insight regarding the development of conceptions throughout the study.

Table 3.7

Targeted Genetics Conceptions Addressed in ERQs, Relevant Bowling et al. (2008) Conceptions and Relevant Study Aspects.

ERQ Sequence	**Question**	**Relevant Bowling *et al.* (2008) Conception**	**Target Conception**	**Relevant Study Aspects**
1	How does a gene for a particular trait actually make that trait happen? For example, how does a gene for dimples make the individual end up having them.	IIIa. Many genes code for proteins, which in turn produce individual traits	Identification of the processes of protein synthesis, transcription and translation, as part of gene expression.	26. Relate micro (gene) to macro (trait) 27. Gene ontology
2	Each type of species has their distinct chromosome number. Humans have a chromosome number of 46, while chimpanzees have a number of 48. If I somehow managed to successfully add 2 pairs of chromosomes to a	Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.	1. Change in chromosome number within a species a result of an error in division in sex cells where the offspring ends up having one more or one less copy of a particular chromosome 2. Different species carry	4. Relate micro (chromosome) to macro (organism) 5. Ontology of chromosomes

	human stem cell so that it will have 48 chromosomes, what do you think will happen? will this cell develop into a chimpanzee cell? why or why not?		3. Organization of genes on chromosomes is not the same across species, and hence adding or removing chromosomes does not switch the organism from one species to another		
3	What is meant by the genetic code is universal? explain how the genetic code is universal.	Ia. DNA is the genetic material of virtually all different types of organisms.	Codons, a set of three nucleotides, codes for the same amino acid across different species.	6.	Ontology of genes
4	In your own words, explain how Genetically Modified Organisms (GMOs) are produced, such as insulin producing bacteria.	VIa. The current and future application of genetics and genetic technology to such areas as health care, forensic analysis,	1. The nature of genetic code, being universal, allows for the insertion and later expression of target genes in host cells. 2. Correct sequence of	3.	Relate micro (gene and microscopic processes) to macro (product)

genetically modified organisms, etc. holds great potential for improving life.	steps involved in genetic engineering

As for the analysis of the student responses, the student responses were analyzed to identify conceptions, then these conceptions were compared to the target conception of the question. If the student held a similar conception to the target conception then it would be considered correct, if not, it was considered a misconception. Identified misconceptions were then categorized and then the frequency of these misconceptions was identified to determine any predominant misconceptions. An example of how this was done is shown in **Table 3.8** for ERQ 1 where the twenty-three participants responded to the question. The misconceptions were also related to the micro/macro/symbolic and ontological aspects. The remaining responses from the ERQ's were analyzed in a similar manner and the conceptions of the students were identified and compared to address the research questions of the study. This is outlined in the next chapter when discussing the results.

Table 3.8

Identified Student Conceptions from ERQ 1 and Study Related Aspects

ERQ Sequence	Question	Correctly Identified Conception	Frequency	Identified Misconception	Related Aspects		Frequency
1	How does a gene for a particular trait actually make that trait happen? For example, how does a gene for dimples make the individual end up having them.	Identification of the processes of protein synthesis, transcription and translation, as part of gene expression.	4/23	Confusion of gene expression with gene transmission	-		13/23
				If a trait is dominant, then it will definitely be transmitted from parent to off-spring and then expressed in off-spring	4.	link micro (gene) to macro (trait)	3/23
				Genes code for a particular trait by directly causing it to happen; no mention of proteins	5.	Gene ontology	2/23
				Genes that determine physical features are randomly switched on/off throughout an individual's life	6.	Gene ontology	1/23

Considerations Prior to Implementing the Study.

Ethical Considerations

Since this study deals with subjects of a sensitive age, it was important to accommodate certain ethical issues. Firstly, since this study deals with evaluating the effectiveness of an instructional approach on IB students, this means that this instruction influences how they learn and hence how they perform on the external assessments of the IB (the exams after the two-year diploma). These considerations included getting the approval of the Institutional Review Board (IRB) of the American University of Beirut, coordinating with the Head of Department and IB Coordinator at The Academy to ensure that the students are still being prepared for the IB assessments, and preparing alternative instruction to support the students in case the instructional approach was not effective.

Consequently, the details of the study and nature of the instruction were discussed in depth with the IB Coordinator of the school and the Head of Department of Science along with the school's administration to obtain the school's approval. Coordination with the Science Head of Department (HOD) and the IB Coordinator (IBC) meant that prior to asking for permission to implement the study from the school administration, the researcher discussed the theoretical component of the study with said HOD and IBC, emphasized the alignment of the instructional plan with the IB requirements for the intended content, and confirmed that that the instructional method would pose no harm in any to students.

Also, prior to implementing the study, the theoretical background of the study was discussed with an experienced colleague. This experienced colleague is a female teacher with twenty-one years of experience in teaching high school science, and six years of experience in teaching IB biology. The role of the experienced colleague included giving feedback on lesson plans about their effectiveness in improving understanding and reviewing the assessment procedures regarding their potency in checking for understanding for the targeted

objectives. Modifications were made according to her suggestions, after discussions and resulting consensus on the aforementioned points.

Alternative instructional materials were prepared in case the instruction implemented in the study did not seem to benefit the students. Even though the instructional approach proposed in the study might have strong potential theoretically, alternative instructional materials were prepared by the teacher in case the instructional approach was not deemed effective. The researcher acknowledged that students might be challenged by the unfamiliar mode of instruction rather than just the content, particularly when encouraged to start categorizing concepts within the micro/macro and symbolic representation format. This was an important aspect to consider given that this mode of instruction is being applied mid-way through the year, and only for four to five weeks. Hence, it was important for the researcher (who is also the teacher) to prepare alternative instructional materials that are more familiar to the students and are similar to how other content has been taught, in case the students did not benefit from the instructional approach. The need for alternative instructional methods was decided based on the weekly assessments (Extended Response Questions) done during the study. If the students were not performing well for two weeks consecutively on those assessments, the study would have been terminated, and the alternative instruction would have been used. In summary, the instructional materials would have focused on addressing the IB objectives for the genetics unit without addressing the multiple representations of the genetics concepts nor their ontological aspect. Based on the student performance during the first two weeks of the study, which indicated that the students did not seem to be facing problems with the implemented instructional approach, the study was continued, and the alternative instructional materials were not used.

Getting the IRB approval is a mandatory step before commencing with a study involving human research subjects. As part of the approval, *Parent Permission forms* and

Adolescent Assent forms were created in both English and Arabic to inform the parents and get their permission to videotape classroom lessons and discussions for research purposes, whilst taking the assent of the students and informing them of what is to happen. The forms included details to reassure the parents regarding how data will be protected through safety precautions and the use of pseudonyms for both the students and the school to ensure the privacy of the students, their families and the school is preserved.

Since the teacher is the researcher and this might have caused the students/parents to feel pressured to partake in the study, several measures were taken to minimize this effect, including having a colleague teacher introduce the study on her behalf to the students and parents. Moreover, the consent process was facilitated by the same colleague who does not teach the targeted students. The researcher first introduced the study and its purpose to the colleague and trained him beforehand on how to introduce a study and ask for consent. This was done using information from the Belmont report, which is the basis of all ethical issues regarding research with human subjects. He was also trained on presenting the consent forms and addressing the sections.

The consenting process followed the following timeline:

1. The colleague was introduced to the study's theory and methodology beforehand. He was then trained by the researcher on presenting the study and recruiting subjects. The training was done a week prior to when the students were to be introduced to the study. This was done so the colleague would have time to ask questions and confirm details.
2. Ten days prior to when the study was meant to commence, the colleague introduced the students to the study details during class.
3. An email was sent that day to the parents giving them background on the study and explaining its purpose. The email also set a date for an after-school meeting during

which the study would be explained, and concerns and questions would be addressed. Consent forms would be given at the end of the meeting.

4. The colleague met the attending students and parents, presented the study, and distributed the consent and assent forms in English and Arabic. Content of the study, along with the concerns and questions were addressed in both Arabic and English.

The researcher was absent during the presentation to further reduce any influence and only returned once the forms were handed out. This was to answer questions and inform parents of her availability via email or the school phone to address concerns and questions at any time.

It was made clear in parent permission forms and adolescent assent forms that choosing not to participate, or participating then choosing to withdraw, would have no consequence whatsoever on the students' learning or evaluation. The researcher made the following explicit in the consent and assent forms, and ensured that it was made clear by the colleague in the meeting that:

5. All students, whether they choose to partake in the study or not, will benefit from the instructional approach used in the study.
6. Students who wish to partake in the study, with or without interviews, will not receive any benefits in comparison to those who do not wish to partake in the study. More explicitly, such decision will not affect:
   a. Their grades in the subject
   b. Their treatment in the class, including their participation in the class to ask questions or contribute to the lessons
   c. Their preparation for any upcoming assessments
7. Students who do not wish to partake in the study will face no consequences whatsoever. More explicitly, such decision will not affect:

a. Their grades in the subject

b. Their treatment in the class, including their participation in the class to ask questions or contribute to the lessons

c. Their preparation for any upcoming assessments

8. Students may decide to drop out of the study at any point, and such decision will not influence:

a. Their grades in the subject

b. Their treatment in the class, including their participation in the class to ask questions or contribute to the lessons

c. Their preparation for any upcoming assessments

At the end of the consenting process, twenty-three out of a total of twenty-four students agreed to participate in the study. Of those twenty-three, five students did not want to be included in the video and were seated accordingly during the filming of the lessons, and nine out of the twenty-three agreed to be selected to be interviewed.

Furthermore, several measures were taken to ensure the privacy of the participants was protected. This encompassed the methods of data collection and analysis. For example, the lessons were recorded by placing the video camera in the back of the class, so no faces were recorded. In the consent forms, the parents and students had the option to choose to be completely omitted from video recording.

As part of the data collection, five students were selected to be interviewed throughout the study to get a better understanding of their feedback on the method, and to get a better understanding of how it has helped/or not in the learning. These five students were selected randomly from the group of students that had consented to being interviewed, which as mentioned were a total of nine students. The initial aim was to have students from different

levels and with different backgrounds (grade 10 honour's and grade 10 regular students); however, this choice was limited due to the consenting participants.

The interviews were audiotaped and transcribed (into text). Classroom lessons discussions were videotaped and then transcribed as well. These transcripts (texts) did not directly mention student names; instead, the students were distinguished by pseudonyms. The pseudonyms were numbers based on the students seating positions in the class.

The students had a fixed seating position throughout the study. This supported both the student who did not wish to partake in the study, and the six students who did not wish to be videotaped, as they were seated in a position outside the video frame. The student who did not wish to partake in the study also had his audial contributions (if captured when videotaping) omitted when the data was transcribed.

Furthermore, during the period of the study, while the data were being collected, hard copies/papers were stored in a locked closet, while digital data were stored on the researcher's password protected laptop in a password-protected folder. The instruments used to record the videos of the lessons and the audio of the interviews were locked in a closet as well. The researcher only accessed this closet. The digital data were sent to the Principal Investigator (PI) by sharing them on a password-protected file on a drop-box. Furthermore, the data was shared with PI, and he ensured that the data was saved safely for a minimum period of three years as required by AUB guidelines.

Validity Considerations

Other than the ethical concerns associated with the potential influence on the participants by the researcher, there were also some validity concerns that were addressed regarding the educator applying the study.

Part of the "success" of this instructional approach would be in its ability to be applied in *any* IB Biology genetics lesson, and to train *any* IB teacher so that she/he can

apply it in their classroom. Having the researcher apply it in her own classroom rather than test its applicability with another teacher is arguably a limitation to the study. However, there are benefits of the researcher applying the instructional approach as shown in literature of similar nature. In one of the studies where the researcher was implementing a study in her class to investigate metacognition and conceptual change, she stated that,

> research was not distinct from practice… implementation of research findings to classroom practice proved to be a mote issue because it occurred simultaneously with and was synonymous with the generation of knowledge and understanding gained from the research (Hennessey, 1999, p.3).

Furthermore, one can anticipate other benefits such as:

1. Because the teacher is the researcher herself, no teacher-training procedures were needed to prepare for the study as the researcher is the most familiar individual with the purpose of the study and how is it applied. Therefore, the researcher cannot claim that the study results were influenced by poor/inconsistent application.
2. The researcher is the class's teacher and is familiar with the students, she would be able to customize the instruction and semi-structured interview better to get further insight regarding the student understanding.

This last point was also mentioned in the aforementioned study as being a strength for the methodology (Hennessey, 1999, p. 3).

In addition to the above perceived benefits, the researcher also kept a reflective journal on the implementation of the study. This journal provided the details of implementing the intervention in the classroom and the feedback of the educator/researcher. The purpose of the reflective journal was to increase transferability of the findings, which is the "degree to which the results of qualitative research can be generalized or transferred to other contexts" (Trochim, 2006). "Transferability is established by providing evidence that the research

study's findings could be applicable to other contexts, situations, times, and populations" (*What is transferability in qualitative research and how do we establish it,* 2020). The journal is available in **Appendix 14**. Furthermore, the researcher used a variety of data sources for the study, allowing for a form of triangulation, thus establishing the credibility of the findings (Winston & Jackson, 1995).

Reliability Considerations

Throughout the study, reliability was established through inter-rater agreement. It is important to note that reliability could not be established in a quantitative manner due to the interpretative nature of the study. The manner in which reliability was established is explained in this section.

Other than giving feedback on lesson plans and class lessons, the aforementioned experienced colleague also aided in refining the instruments and in the data analysis. This process involved two main aspects:

1. Analyzing the instruments for what concepts they addressed.
2. Analyzing the student responses to identify their conceptions.

Some of instruments used had their own analytical framework such as the GLAI and the two-tier questionnaire, however the interview and the extended response questions did not. Hence, it was important to review these questions with another more experienced colleague to ensure that these instruments are fulfilling their intended purpose in measuring a particular aspect.

Analyzing the questions. Throughout the study, there was a total of four sets of interviews and four sets of Extended Response Questions (ERQs), each set was given at a particular time during the study (before, during and after). Each interview set was made up of five to ten questions, and this number varied within each set, as the interviews are semi-structured and depended on the interviewee. Furthermore, the interview questions sometimes included questions on the perception of the students of the instruction. These questions were

not analyzed for conceptions but used to provide insight on student perspective on their own learning. As for the extended response questions (ERQs), the students were asked one question per set. The interview questions and the four ERQs were analyzed in the manner described below.

Prior to analyzing the instruments, the researcher and the experienced colleague discussed the theoretical underpinnings of the study since the colleague aided in reviewing the study's lesson plans and instruments (as mentioned under the ethical considerations). To establish reliability of the instruments in regards the conceptions they addressed, the researcher followed the following process:

1. the researcher compiled all sets of interviews and extended response questions (used throughout the study) and divided them into three sections.
2. The researcher then shared the first set of interview questions and extended response questions with the experienced colleague, and for each question the researcher and the colleague discussed:
    a. what conceptions did this question address?
    b. whether the question had micro/macro/symbolic/ontological elements.

To determine what conceptions were addressed, the researcher and the experienced colleague first linked the questions to what conceptions they addressed from the list adapted from Bowling *et al.* (2008), as that list compiles topics and sub-topics that relate to genetic literacy. After agreeing on what conception is addressed from the Bowling *et al.* (2008) list, the researcher and the colleague then discussed how these adopted conceptions can be elaborated or modified to fit the ERQs and/or interview questions more specifically. After agreeing on what conceptions were addressed in the questions, the researcher and the colleague then discussed whether these conceptions can be linked to micro/macro/symbolic or ontological elements.

1. After discussing the aforementioned and reaching an agreement on the first set of questions, the researcher and the colleague then analyzed the second set of questions similarly to the first, however this process was done independently.
2. After completing the second set of questions and addressing the conceptions and micro/macro etc. elements, the researcher and the colleague then met to discuss their analysis, identify differences and discuss them until consensus was reached for all the second set of questions.
3. After consensus was reached, the researcher analyzed the remaining third of the questions by herself.

The analysis of the questions, the conceptions addressed by each question, is described in the upcoming section when describing the data collection instruments.

Analyzing the responses. A similar method was used to analyze student responses from the interviews and the extended response questions, yet the analysis was slightly different as the data from the interview sets were from five students, whereas the ERQs were from all the participants (twenty-three). The purpose of the response analysis was to identify the student conceptions displayed in the student responses, whether it being through answering the interview questions, or answering the extended response questions.

Interview analysis. For the interview analysis, the researcher first compiled the responses of the five interviewees from all four sets of interviews. Two interviews from each set were shared with the experienced colleague (two student interviews out of the total of five student interviews per one set). These responses were analyzed cooperatively by both. The concepts identified in the student responses were listed and then compared to the conceptions that were targeted by the interview questions to see if the student was able to address the target conception, and if he did not, what alternative conception did he hold. Alternative conceptions compiled were summarized as a list by the researcher and the colleague so the

frequency of the alternative conceptions could be measured. In summary, the researcher and experienced colleague met to discuss the results of the analysis and reached a common understanding of the nature of the analysis.

Then, after the researcher and colleague agreed on the conceptions identified in two of the responses from each of the four sets, one more interview from each set was shared with the experienced colleague. The researcher and experienced colleague analyzed these interviews in a similar manner as the previous two sets, however they did so independently. The researcher and the experienced colleague then met to share their analysis. Discrepancies in the analysis included different phrasing of particular conceptions, however the idea was similar, and after some discussion consensus was reached regarding the analysis. The remaining two sets of interviews (out of five) from each of the four sets were analyzed by the researcher using the same established aforementioned system. The responses analyzed by the researcher mostly fit the already established list prepared in cooperation with the colleague.

Extended-response question Analysis. As for the ERQ analysis, since there was a total of four sets, with one question in each, and around twenty-three responses per question, the analysis was slightly different but followed a similar process. The researcher first compiled the responses all four sets of the extended response questions and shared five responses from each set with the experienced colleague. These responses were analyzed cooperatively by both. The concepts identified in the student responses were listed and then compared to the conceptions that were targeted by the ERQ question to see if the student was able to address the target conception, and if he did not, what alternative conception did he hold. Alternative conceptions compiled were summarized as a list by the researcher and the colleague so the frequency of the alternative conceptions can be measured. In summary, the researcher and experienced colleague met to discuss the results of the analysis and reached a common understanding of the nature of the analysis.

Then, five more responses from each set were shared by the researcher with the experienced colleague. The researcher and experienced colleague analyzed these responses in a similar manner as the previous five sets, however they did so independently. The researcher and the experienced colleague then met to share their analysis. Discrepancies in the analysis included small details and were sorted through a brief discussion until consensus was reached regarding the analysis. The remaining responses from the four sets of ERQs were analyzed by the researcher alone using the same established aforementioned system. The responses analyzed by the researcher mostly fit the already established list done in cooperation with the colleague. The analysis of the student responses is discussed in the upcoming chapter.

CHAPTER IV

RESULTS

In this chapter, the data collected throughout the study has been analyzed to answer the following research questions:

1. What misconceptions do year 1 Diploma Program students have regarding genetics?

2. What is the influence of a modified multiple representation instruction that integrates the ontological aspect on the understanding and learning of the students?

Firstly, the context at which this study took place has been introduced, then the data from pretests [the genetics literacy assessment items (GLAI) and two-tier questionnaire], the first interview, and an extended response question have been analyzed to identify student misconceptions and hence address the first research question. The second research question has been addressed by analyzing data from consecutive tests (GLAI and two-tier questionnaire), extended response questions and interviews done throughout the study, and lastly, interaction in the classroom and teacher reflections during the lessons. These have been elaborated on in greater depth when addressing the second research question.

To answer the first question, data from pre-tests have been analyzed to detect students' misconceptions prior to being exposed to the intervention. These pre-tests include a genetic literacy assessment items (GLAI) and a two-tier questionnaire. An extended response question (ERQ) and a semi-structured interview (SSI) that were done before the study commenced were also analyzed. These instruments will be discussed in greater detail later in this section. As for the second question, which focuses on the influence of the intervention on student conceptions, the misconceptions identified in the aforementioned pretests, extended response question and interview (that addressed the first research question) have been compared with the post tests, a GLAI test administered during and after the study, a Two-Tier

questionnaire administered at the end of the study, and extended-response questions (ERQ's) and semi-structured interviews (SSI's) done throughout and after the study. Furthermore, misconceptions have been identified and compared from the data collected throughout the study through students' engagement in the class. The class is made up of twenty-four students, of those twenty-four, one student chose not to partake in the study. Therefore, the upcoming sections will discuss results from a sample of twenty-three students.

Study Context

Before delving into the results of the study, it is important to describe the context in which this study took place. This study took place a few weeks prior to the Corona (COVID-19) virus outbreak. In summary, two-thirds of the study were done in a classroom context, while the last third was done online. The last third of the study was conducted online as per governmental restrictions due to regulations from the Kuwaiti Ministry of Education (Henceforth "Ministry" will be used) regarding online teaching during the outbreak. Furthermore, directly before the outbreak, students were already on vacation as part of spring-break, and hence by the time school had clear instructions regarding online teaching, two weeks had already passed without instruction. This two-week gap in instruction may have had an influence on the data during the last third of the study.

Ministry and School Regulations

Towards the last third of the study, news on the COVID 19 virus outbreak started spreading toward the end of spring break. At the time, the Ministry immediately issued a decision on suspending school for a week as a safety precaution. Teachers were not allowed to give work during that week, as it was expected that schools will resume after that period. However, as the week progressed, it became clearer that the issue was more serious than initially anticipated, hence, dates for school re-opening were postponed, and new decisions were made by the government.

During the first weeks of quarantine, the Ministry prohibited the teaching of new material. As a result, teachers were only allowed to review content given before. As for assigning work, the assignments were to be restricted to review assignments, which were optional in nature and not meant to be assessed. This meant that students had the option to complete these assignments, and in the case that they did, they would not be assessed or earn grades. As the quarantine proceeded, new governmental decisions were made allowing new material to be taught to complete the year's curriculum for those who wished to continue their learning. However, even if students wished to continue their learning, no assessments were to be given. Furthermore, students could only earn grades higher than their current grade, meaning regardless of the quality of the work submitted, students were to earn an equal or higher grade than their current one. As for those who did not wish to partake and/or continue their learning, they would be given the option to resume their learning in early August, where they can compensate the material they did not complete. Consequently, student motivation and performance were largely impacted by the situation and accommodations.

Student Performance

The general situation, including the decisions made by the Ministry, impacted student engagement and performance to a great extent towards the last third of the study. Since students were aware of the aforementioned regulations, they knew that even with minimal effort they can manage a grade equal to or higher than their current one. This resulted in discrepancy in student number in the remaining online sessions (lessons), and in assignment submissions. Many students did not commit to attending the last lessons which were given online. The few students who still attended the sessions were not consistently submitting the work, and when they did, the work was of significantly lower quality. The aforementioned context is significant to keep into consideration when analyzing the data.

Data Analysis

In the upcoming sections, data collected throughout the study has been analyzed to address the study's research questions. The first section presents the analysis of data collected from the pretests (pre-GLAI, pre-Two-Tier), pre-ERQ, and pre-SSI to address the first research question regarding the student misconceptions. After establishing these misconceptions, data from consecutive GLAI tests, Two-Tier questionnaire, ERQ's and SSI's done throughout the study have been analyzed to identify how student conceptions change throughout the study. This addresses the second research question regarding the influence of the study on student conceptions.

Student Misconceptions Identified in Pre-tests

In this section, the first question is addressed. To answer the first question, data from the pretests, pre-ERQ and pre-SSI were analyzed to detect the misconceptions that grade 11 year 1 IB Biology students have. The pretests include, a GLAI and Two-tier questionnaire, which were two multiple choice questionnaires administered prior to the commencement of the study. The ERQ was an extended-response question given to the students before the lessons started that the students could answer with a short paragraph, and a semi- structured interview done with a one fifth of the class to gain more insight regarding their conceptions.

Genetic Literacy Assessments Items (GLAI) Test. The GLAI was conducted three times in total throughout the study, before the study, during the third week (on the day before spring break), and after the study ended. During the first administration of the test, which was done in class, twenty-three out of twenty-three students participated. During the second administration, which was right before the spring break, twenty students participated, and in the last test, which was done online at the end of the study, fifteen students participated. This discrepancy in student number participation will be discussed in the next section when addressing the second research question.

A description of the GLAI has been provided in the previous chapter along with a description of how the GLAI was analyzed. In summary, the concepts and sub concepts identified per item were used to identify areas of misconceptions of the students. In addition to the listed sub concepts per item, the options per multiple choice question provided further guidance regarding the nature of students' misconceptions. In Table 4.1, student misconceptions have been identified using the same method outlined in chapter three (Table 3.2).

Table 4.1

Genetics Misconceptions Held by Year 1 Diploma Students as Identified by the Pretest GLA Test

Question		Frequency of students who answered correctly	Frequency of students who gave incorrect answers	Related concept (in accordance with concepts set by Bowling *et al*., 2008)	Misconception(s)		Study Related Aspect (links to Macro/Micro/Symbolic and Ontological aspects)	
1.	What is the relationship among genes, DNA, and chromosomes?	16	7	**Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.**	2. 3. 4. 5.	There is no relationship between genes, chromosomes and DNA There is only a relationship between genes and chromosomes but not DNA There is only a relationship between genes and DNA but not chromosomes Genes are composed of chromosomes	6. 7.	Microscopic Ontology of the terms in regard to how they relate
8.	Adult height in humans is partially determined by our genes. When environmental conditions are held constant, humans have a wide variety of heights (not just short, medium, and tall). Height is probably influenced by:	12	11	**IIIc. Most human traits, including diseases, result from the products of multiple genes interacting with environmental variables: examples include height, heart disease, cancer, and bipolar disorder.**	9.	Adult height, which is a trait with varying outcomes, is controlled by a single gene and/or is represented by 2 alleles	-relating macroscopic (height) to micro (gene)	
10.	Our understanding of how genes function indicates that:	12	11	**IIIa. Many genes code for proteins, which in turn produce individual traits.**	11. 12.	Gene products could be carbohydrates and fats Species use different mechanisms to express genes	-microscopic (gene) - ontology of gene (function)	
13.	What is the most likely way the genetic system (genetic material and the genetic code) of living organisms evolved?	8	15	**Ia. DNA is the genetic material of virtually all different types of organisms.**	14. 15. 16.	The same genetic system repeatedly developed at different times in various organisms. One genetic system developed early in the evolution of life in all organisms and remained. One genetic system developed but well after numerous different species existed.	18. 19.	Linking micro (genetic code) to macro (evolution/ differences between species) Ontology of genetic code

					17.	Different genetic systems evolved in different species.		
20.	Which of the following is INCORRECT regarding meiosis?	12	11	**IIa. Chromosome number is reduced by half during meiosis, which results in the formation of genetically different gametes.**	21.	Meiosis happens in both sexual and asexually reproducing organisms	26. 27. 28. 29.	Micro (meiosis) Link micro (meiosis) to micro (cell) Link micro (meiosis) to macro (organism) Ontology of meiosis
					22.	Meiosis maintains the chromosome number after the division in sex cells		
					23.	Meiosis changes the number of chromosomes across generations		
					24.	Produces (genetically) identical cells		
					25.	Can happen to any cell in the body		
30.	Sometimes a trait seems to disappear in a family and then reappear in later generations. If neither parent has the trait, but some of the offspring do, what would you conclude about the inheritance of the trait?	16	7	**IIb. Understanding Mendelian patterns of inheritance, and their biological basis, allows probability statements about the occurrence of traits in offspring**	31.	A parent passes down two copies of a particular gene	34.	Link micro (gene) to macro (organism)
					32.	If an individual has a trait and it is dominant it does not show	35.	Ontology of a gene
					33.	For a recessive trait to be passed down to the offspring, it is enough that one parent has one or two copies of the gene.		
36.	An individual is found to have a mutation in a gene associated with breast cancer. In which cells is this form of the gene located?	4	19	**Id. virtually all cells within an individual contain the same genetic constitution- Different cells and tissues are produced through differential gene activity.**	37.	Mutations affecting a particular organ only happen in the cells/tissues of that organ	39. 40.	Link micro (mutation) to micro (cells) Link micro (mutation) to macro (organism)
					38.	Mutations that affect a particular gender can only exist in cells of that gender		
41.	Mutations in DNA occur in the genomes of most organisms, including humans. What is the most important result of these mutations?	7	16	**Ib. Occasional errors in DNA structure and replication result in genetic variation.**	42.	Mutations produce new genes/ chromosomes /enzymes /cells for the organism	43. 44.	Link micro (mutation) to micro (gene/ enzyme/ chromosome/ cells) Link micro (mutation) to macro (organism)
45.	Multiple genes are associated with complex diseases such as cancer and mental	13	10	**IVb. There are other genetic variations that result in disease less consistently, for example, the**	46.	Having a certain gene means you will have the trait/outcome	Link micro (genes) to macro (disorder)	
					47.	Having a certain gene means you will		

	disorders. When an individual is tested for these genes, what do the results indicate?			**BRCA1 mutation associated with breast cancer.**		already have the trait/outcome		
48.	Which of the following is a current benefit of the application of genetics and genetic technology to health care?	17	6	**VIa. The current and future application of genetics and genetic technology to such areas as health care, forensic analysis, genetically modified organisms, etc. holds great potential for improving life.**	49.	Genetic technology directly relates to finding cures for genetic diseases rather than detect them	Link micro (genes/genetic code) to macro (organism/society)	
50.	A woman has been told she carries a mutation associated with breast cancer. How does this influence her likelihood of developing breast cancer?	16	7	**IVb. There are other genetic variations that result in disease less consistently, for example, the BRCA1 mutation associated with breast cancer.**	51. 52. 53.	Having a gene associated with breast cancer means the individual will most likely NOT get the disease Having a gene associated with breast cancer means the individual will definitely get the disease Having a gene associated with breast cancer means the individual already has the disease	54.	Link micro (mutation) to macro (organism)
55.	Many geneticists study the genetic material of organisms such as mice, fruit flies, and yeast. They are able to apply what they learn from these organisms to humans because virtually all different types of organisms:	15	8	**Ia. DNA is the genetic material of virtually all different types of organisms.**	56. 57.	To study and apply study results across different organisms they should have the same amount of genetic material Having DNA as the structural component is enough to draw comparisons and apply results across different organisms	58. 59.	Link micro (genetic code) to macro (organism) Ontology of genetic code
60.	As HIV has spread around the world, we know some	15	8	**Va. Genetic variation is the rule rather than the exception in**	61.	Genetic changes that provide resistance are produced in	62.	Link micro (genetic differences) to

	individuals are resistant to the effects of the virus even though they are HIV positive. Why?			**the living world and is the basis for evolution by natural selection: without genetic variation there can be no differential selection, and no survival of any species.**		response to infection by the virus.		macro (organism/ resistance)
63.	Which of the following is a characteristic of mutations in DNA?	5	18	**Ib. Occasional errors in DNA structure and replication result in genetic variation.**	64. 65. 66. 67.	They are always beneficial They are always harmful They always have an effect/are expressed Occur at high rates	68. 69. 70.	Micro (mutations) Ontology of mutations Link micro (mutation) to macro (organism)
71.	What is the relationship between DNA and chromosomes in higher organisms?	15	8	**Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.**	- Chromosomes are found within DNA. - There is no difference between DNA and chromosomes - chromosomes produce DNA - DNA and chromosomes are completely separate structures.		72. 73. 74.	Microscopic (DNA, chromosomes) Link micro (DNA, chromosomes) to macro (organisms) Ontology of genes in context of DNA and chromosomes
75.	Huntington's disease is a genetic disorder caused by a dominant gene. Symptoms begin in adulthood and the disease is ultimately fatal. What is an ethical dilemma presented by Huntington's disease when a parent is diagnosed with the disease?	12	11	**VIb. Like all technologies, genetic technologies are fallible and have unintended consequences, some of which can be harmful to individuals, families. or groups.**	76.	Ethical issues arise when an individual is tested for a particular genetic disease	Link Micro(genes) to macro (organism, society)	
77.	Regarding complex traits such as IQ, lung cancer, prostate cancer, etc., how do geneticists describe the contributions of ones' genetic makeup and the environment?	3	20	**IIIc. Most human traits, including diseases, result from the products of multiple genes interacting with environmental variables: examples include height, heart disease, cancer, and bipolar disorder.**	- the environment plays the largest role in actualizing a trait - most traits are determined heavily by genetics with the environment having little effect on complex traits. d. The environment plays a major role in determining complex traits - Genetic differences among humans are so minor that essentially all variations observed among individuals are due to the environment in which they were reared.		78.	Link micro (genes) to macro (trait, organism)

79.	How is the expression of genes regulated or controlled?	8	15	**IVc. Much of gene regulation involves turning genes on and off at the right time.**	- The expression of genes is not regulated or controlled. - Genes are turned on during development and stay on throughout one's life. - Genes are only turned on and off during development. - The expression of genes is only controlled by external factors.	Ontology of genes	
80.	If an individual has a genetic test for a mutation causing a particular disease, and the result is positive, what will that most likely mean?	9	14	**IVa. Some genetic variation results in disease in virtually every environment, for example, the mutations associated with Huntington disease, Tay-Sachs disease, and cystic fibrosis.**	- The individual will definitely exhibit the disease, regardless of whether it is due to a dominant or recessive mutation. - The individual will definitely exhibit the disease only if it is due to a dominant mutation. - A positive test for the mutation indicates that the individual already has the disease. - The environment during the individual's development will be the primary determinant of whether the individual exhibits the disease.	81. 82.	Link micro (mutation) to macro (organism) Ontology of mutations
83.	What effect, if any, does an individual's environment have on the development of his or her traits?	7	16	**IIIb. The functions of a gene and its protein product can be affected by the environment at one or many steps involved in producing a given trait.**	- the environment has little or no effect on most traits in an individual. - It sets the potential for the development of most traits in an individual. - It is a dominant factor for determining most traits in an individual. - It does not have any effect on an individual's traits but can have an effect on the traits of an individual's offspring.	84. 85. 86.	Link micro (gene) to macro (organism) Link macro (environment) to macro (organism) Link macro (environment) to micro (gene)
87.	Your muscle cells, nerve cells, and skin cells have different functions because each kind of cell:	18	5	**Id. virtually all cells within an individual contain the same genetic constitution-Different cells and tissues are produced through differential gene activity.**	- different types of cells carry different kinds and/or numbers of genes that determine their function. - function of a cell is determined by its location - different types of cells arise due to different mutations.	88.	Link micro (gene) to micro (cells)
89.	At what times during an individual's life does the environment influence the expression of his or her genes?	0	23	**IIIb. The functions of a gene and its protein product can be affected by the environment at one or many steps involved in**	- environment influence the expression of genes only after birth till adulthood - environment influence the expression of genes only after birth till the rest of the individual's life - environment has an effect of genes only during key stages	90. 91.	Link macro (environment) to micro (gene) Link macro (environment) to macro (organism)

				producing a given trait.	of life such as puberty and menopause. - Environment has little or no effect on how genes are expressed.		
92.	Which of the following is INCORRECT regarding the genetic differences among ethnic groups?	2	21	**Vb. Genetic variation is much greater within traditional human ethnic groups than among them. Superficial phenotypic differences do not reflect the high degree of genetic relatedness among traditional ethnic groups**	- The DNA sequence is substantially different among humans - Genetic differences responsible for skin color represent a substantial portion of the human genome.	93.	Link micro (DNA sequence) to macro (organisms)
94.	What is the relationship between genes and traits expressed in individuals?	9	14	**IIIa. Many genes code for proteins, which in turn produce individual traits.**	- Genes code for DNA - Genes code for chromosomes - Genes code for carbohydrates - The environment rather than genes is primarily responsible for individual traits.	95.	Link micro (genes) to macro (traits of an organism)
96.	Which of the following does NOT accurately reflect Charles Darwin's basic principles of evolution?	10	13	**Va. Genetic variation is the rule rather than the exception in the living world and is the basis for evolution by natural selection: without genetic variation there can be no differential selection, and no survival of any species.**	- The capacity of biological species to reproduce is limited. - The capacity of the earth to sustain continuous population growth is unlimited. - individuals are equally equipped to survive changes in the environment.	97.	Link micro (genetics) to macro (organisms)
98.	Which of the following is NOT considered an ethical or legal concern?	4	19	**VIc. Science often can tell us what we can or cannot do, but it does not always indicate clearly what we should do. Those decisions arise from the intersection of science with ethics, the law. and public policy.**	- Allowing prenatal sex selection is not an ethical concern. - There are no ethical or legal concerns regarding counseling couples not to have abnormal babies that require costly care. - There are no ethical or legal concerns regarding utilizing embryonic stem cells for research. - There are no ethical or legal concerns regarding giving insurance companies the right to deny insurance to those individuals known to have a high risk or genetic disease. - Offering mothers 35 years of age or older the opportunity to have prenatal diagnosis for	99.	Link micro (genetics) to macro (organisms/society)

						chromosome anomalies is controversial.		
100.	Cystic fibrosis (CF) is a recessive disorder, meaning that an individual must have two copies of an abnormal CF gene to be affected. What is the probability that a child of two individuals who each have one copy of the abnormal gene will be affected with CF?	14	9	**IIb. Understanding Mendelian patterns of inheritance, and their biological basis, allows probability statements about the occurrence of traits in offspring.**	101.	For an individual to be affected by a recessive disease, it is enough to inherit one copy of the recessive allele from one parent	102.	Link micro (gene/mutation) to macro (trait/organism)
103.	Which of the following is a correct statement about science and the scientific method?	18	5	**VIc. Science often can tell us what we can or cannot do, but it does not always indicate clearly what we should do. Those decisions arise from the intersection of science with ethics, the law. and public policy.**	104. 105. 106. 107.	science and the scientific method are rarely able to provide explanations of the natural world. science and the scientific method provide explanations that include the supernatural world. science and the scientific method are unlikely to contribute significantly to improving the human condition. conclusions reached by science and the scientific method are not open to question in the light of new data and observations.	-	
108.	The muscle cells of humans contain 46 chromosomes. How many chromosomes do unfertilized human egg cells contain?	19	4	**IIa. Chromosome number is reduced by half during meiosis, which results in the formation of genetically different gametes.**	109. 110. 111.	Body cells and sex cells carry the same number of chromosomes Sex cells carry twice as many chromosomes as body cells Body cells carry four times more chromosomes than sex cells	112.	Link micro (chromosome) to micro (sex cell)
113.	What is an example of an unexpected consequence when current	5	18	**VIb. Like all technologies, genetic technologies are fallible and have**	114.	Genetic technologies are very specific in regard to what is being screened	115.	Link micro (genetics) to macro (organisms)

genetic technologies are used?	**unintended consequences, some of which can be harmful to individuals, families. or groups.**

Summary of Misconception held by Year 1 Diploma Students as Identified in the pre-GLAI Test. Out of the thirty questions, there were fourteen questions that most students (twelve or more students out of twenty-three) did not answer correctly. Those questions were numbers 4, 7, 8, 14, 17, 18, 19, 20, 22, 23, 24, 25, 26, and 30. Out of those fourteen questions, numbers 23, 25, 26 and 30 discussed concepts that were unfamiliar (not directly relevant to the content of genetics in IB) to the students such as ethnicities (23), evolution (25), ethical and legal concerns (26) and genetic technology (30), and hence will not be regarded with importance as other items that are more familiar to the students. Of the remaining ten questions, eight questions addressed the link between the micro aspect to the macro aspect. Furthermore, four questions addressed the topic of mutations and three addressed the link between the environment and genetics.

When examining items that the students performed the poorest on, it is noticeable that topics relating to Nature of the Genetic Material (I) and Gene Expression (III) were the most conceptions that the students did poorly on. Specifically, when looking at the items, two main sub-conceptions stand out.

1. **Ib.** Occasional errors in DNA structure and replication result in genetic variation.

2. **IIIc.** Most human traits, including diseases, result from the products of multiple genes interacting with environmental variables: examples include height, heart disease, cancer, and bipolar disorder.

In regard to the nature of genetics, students seem to be specifically confused by the concept of mutations. Students seem to have misconceptions regarding what causes mutations and how they affect the individual in general. Many students think that mutations happen at random and might at any point affect the organism as a whole. Furthermore, students also seem to consistently associate mutations with negative consequences, even though most mutations have negligible effects and rarely have a positive influence. The role

of mutations in promoting variation within populations and species is also overlooked as shown in the test results.

Furthermore, as mentioned above, students struggled with items addressing the sub-concept of gene expression and the role of the environment. Among the misconceptions surrounding this sub concept, students seemed to mainly struggle with the nature of genes. Most seemed to think that genes are determinant of the traits they code for, with the environment playing little or no role in actualizing those traits. Furthermore, many students seemed to struggle with the process of gene expression through protein synthesis. In summary students were challenged by the concepts addressing the ontology of genes and the link between micro and macro concepts.

Two-Tier Questionnaire. The Two-Tier Questionnaire was administered twice throughout the study, once before the study and once after the study. During the first administration of the questionnaire, which was done in class, twenty-three out of the twenty-three students participated. During the second administration, which was done online at the end of the study, only fourteen students participated. Similar to the GLAI pre-test, all students participated in the pre-two-tier questionnaire and this test was analyzed to identify student misconceptions and address the first research question. The method of analysis was discussed in chapter III. **Table 4.2** shows the results of the students on the seven items of the two-tier questionnaire.

Table 4.2

Genetics Misconceptions Held by Year 1 Diploma Students as Identified by the Pretest Two-Tier Questionnaire

Question	**Frequency of students who answered the item correctly (out of 23)**	**Reasoning Type**	**Study Related Aspect per Item**	**Misconception held by the student**	**Justification**
Item 1, Tier 1: The trait, curly hair, is dominant to straight hair. If we use "C" to represent the dominant allele (gene) for curly hair and "c" for the recessive allele, would a person with genotype Cc have curly hair?	16	Cause-to-effect reasoning. Mapping genotype to phenotype	Linking Symbolic to Macro	Heterozygous genotype (Cc) does not express the dominant trait Dominant trait is only expressed in homozygous form	6. Failure to recognize that dominant traits are expressed in both heterozygous and homozygous form symbolized by Cc and CC (genotype).
Item 1, Tier 2: Reason for the above [Item 1, Tier 1]?				7. The person needs to have CC for curly hair. 8. The person may or may not have curly hair. 9. The recessive allele c is expressed.	10. Failure to recognize that presence of one dominant allele, symbolized by "C" is enough to express the dominant trait
Item 2, Tier 1: Which of the following best describes the trait in the following pedigree?	10	Effect-to-cause reasoning: Monohybrid inheritance: Mapping phenotype to genotype	11. Linking Macro to Micro/Symbolic	12. A dominant allele can be present in the parents, not show, and be passed down to off-spring and show	13. Failure to map from phenotype to genotype between generations using a pedigree chart
Item 2, Tier 2: Reason for the above:			14.	15. The trait is recessive Only one of the three children in the second generation has the trait. 16. The trait is dominant because both the female in the first generation and her son have the trait. 17. The trait can be either recessive or dominant based on the pedigree.	18. Failure to identify the male individual in the third generation having two recessive alleles in his genotype that must have come respectively from his two parents, who were heterozygous for the trait and thus did not show the trait.
Item 3, Tier 1: The following shows a "Black Box" that provides a simplified model to show a process in genetics. What does the "Black Box" represent?	6	Process reasoning: Punnett squares (input/output reasoning): Meiosis process (event	19. Linking symbolic and Micro	20. The image shown to divide the cell into four cells with half the number of the original chromosome number represents fertilization	22. Failure to identify the "black box" as an analogy representation of meiosis—the reduction cell division for

		reasoning) Mitosis process			21. Represents a cell division that occurs after fertilization	producing haploid sperms or eggs.
Item 3, Tier 2: Reason for the above [Item 3, Tier 1]?			23.		24. Different combinations of chromosomes are responsible for the different cells and function in the body 25. Cells divide to form different cells with varying chromosome number to fulfill different functions	26. Students did not understand the processes of meiosis and fertilization and their roles in maintaining the constant diploid number of chromosomes in a species from generation to generation.
Item 4, Tier 1: Which one of the following is the best description of a gene?	7	Process reasoning: Mapping information in DNA base sequence (genotype) to amino acid sequence in protein synthesis (phenotype)	27.	Ontology of a gene	28. Genes are the smallest unit of structure in a chromosome. 29. Genes are a segment in a DNA molecule.	Understanding genes as an instruction unit rather than structural, that codes for particular instructions/traits
Item 4, Tier 2: Reason for the above [Item 4, Tier 1]?			30.		31. Genes are defined in regard to the structural role they play in composing chromosomes 32. Genes are defined as being structurally made up of DNA	Genes are units of information in chromosomes rather than structural units, made up of DNA and code for proteins
Item 5, Tier 1: The pedigree chart below shows the inheritance of a common genetic disease in Western Australia. Which of the following best describes the allele that gives rise to the trait?	4	Effect-to-cause reasoning: Monohybrid inheritance: Mapping phenotype to genotype	33.	Linking Macro to Micro/Symbolic	34. Disease is sex-linked dominant 35. Disease is sex-linked recessive 36. Disease is autosomal dominant	Identifying different modes of inheritance (sex-linked vs autosomal) and failure to map from phenotype to genotype between generations using a pedigree chart whilst considering the gender (similar to item 3)
Item 5, Tier 2: Reason for the above [Item 5, Tier 1]?			37.		38. If both a female and male are affected by a disease, then it must be autosomal 39. If the parents are normal but one of the offspring is affected, then the disease is definitely autosomal recessive	For a disease to be sex-linked, the males affected must inherit the disease from their mothers, and for the female to be affected, both parents must be carriers of the disease and hence the father must have it
Item 6, Tier 1: Some dogs bark when following a scent, others are silent and are called silent trackers. Barking is dominant (allele B) to non-barking (allele b). A hunter owns a barker which he wants to use for breeding purposes. However, he wants to be sure it has a genotype of BB. What is	2	Cause-to-effect reasoning; Monohybrid inheritance: Mapping genotype to phenotype	40.	Linking Symbolic/Micro to Macro	41. To check whether an organism is heterozygous or homozygous dominant, crossing with another homozygous dominant will yield observable results 42. To check whether an organism is heterozygous or homozygous dominant,	43. Understanding the interaction of dominant and recessive alleles and how alleles are passed down from parents to offspring. 44. Using phenotype of offspring to determine parental genotype

the genotype of the bitch he should mate with this dog?					crossing with another heterozygous will yield observable results	
Item 6, Tier 2: Reason for the above [Item 6, Tier 1]?		45.		46. If no silent trackers appear in the offspring, he can be sure that his dog's genotype is BB. 47. - If the dog is Bb, the chances of getting silent trackers in the offspring are zero.		Understanding that if recessive trait is expressed in offspring then offspring must have inherited it from both parents meaning both parents must be carriers or homozygous recessive.
Item 7, Tier 1: Peter is an albino who was born without the ability to make a pigment in the skin. Albinism is a recessive characteristic. Suppose we use "A" for the dominant gene (allele) and "a" for the recessive gene, what would be Peter's genotypes (genes) for albinism?	12	Effect-to-cause reasoning: Mapping phenotype to genotype	48.	Linking Macro to Symbolic	49.	Recessive traits can be expressed in heterozygous form	For a recessive trait to be expressed both alleles must be recessive.
Item 7, Tier 2: Reason for the above [Item 7, Tier 1]?			50.		51. 52.	Having one copy of recessive allele is enough to express recessive trait In heterozygous form, the recessive allele is expressed	Having only one recessive allele is not enough to cause albinism

Summary of Misconception held by Year 1 Diploma Students as Identified in the two-tier Questionnaire (pretest). From **Table 4.2,** the items on which the students performed the poorest can be identified, along with their corresponding reasoning type and relevant study aspects. In general, the students did not score too well on the two-tier questionnaire as the questionnaire required them to answer both tiers correctly to score the item correctly. Based on the table above, the students did most poorly on items 3,4,5 and 6. Item 3 addresses the role of meiosis in producing four genetically different cells through the use of the "black-box analogy" which relates the symbolic aspect to the micro aspect, item 4 addresses the description of a gene which relates to the ontological aspect of a gene, item 5 involves a pedigree that requires higher level reasoning that relates the macro aspect to the symbolic, and item 6 involves the understanding of the use of the "test-cross" to check whether an organism expressing a dominant trait is homozygous or heterozygous for that trait which relates micro to macro aspects. It is expected that students would not perform well on items that require a higher level of reasoning as they are more challenging. In this case, items 3 and 4 on the test addressed higher levels of reasoning (level V and level VI). However, the results show that students also struggled with items 5 and 6 on the test which are categorized as lower levels of reasoning. It is important to point out that both items 5 and 6 had two options on the second tier that might have been misleading to the students. On item 5, 2 of the options are accurate but one is more accurate than the other as the other option, even though is true, is insufficient to support the answer. Item 6 asked, "Some dogs bark when following a scent, others are silent and are called silent trackers. Barking is dominant (allele B) to non-barking (allele b). A hunter owns a barker which he wants to use for breeding purposes. However, he wants to be sure it has a genotype of BB.". The first tier asked the students, "What is the genotype of the bitch he should mate with this dog?", and the second tier asked the student to rationalize their answer from tier one with either of these three options:

[] 1. If any silent tracker appears in the offspring, the hunter can be sure that his dog's genotype is Bb.

[] 2. If no silent trackers appear in the offspring, he can be sure that his dog's genotype is BB.

[] 3. If the dog is Bb, the chances of getting silent trackers in the offspring are zero.

Option one and option two are both accurate in regard to rationalizing the first-tier answer, however option one is *more* correct. This is because if no silent trackers appear , this is no guarantee that no silent trackers will appear in future offspring, whereas in the first option, the presence of a single silent tracker immediately disputes the genotype is BB, and hence it is certainly Bb instead. Many students did not answer the sixth item correctly due to this mix-up.

Furthermore, errors on item 4 on the two-tier questionnaire indicate that students struggle with the concept of a gene and how it relates to other genetic-related concepts. This was also shown in the GLAI results which emphasizes the students' struggle with the ontology of the gene. It is interesting to note that the students score best on the item which links between the symbolic and macro aspects. This can be attributed to the method of teaching in genetics where often the symbolic (genotype) is linked directly to the macro (the trait).

Interviews at the Beginning of the Study. Semi-structured interviews were administered before, during and after the study. As indicated in Chapter 3, five students were consistently interviewed throughout the study. Ideally, those students would be divided between students who were previously in the honor's class and students who were in the regular class, however due to selection of volunteers the result was slightly different. Of the five students, only one student was from the regular class (student 8), whereas the remaining four were from the honor's class (students 15, 16, 20 and 22). In this section, the first set of interviews are analyzed to identify student misconceptions. The questions for interview 1 and

student responses are presented in Table 4.3. Concepts addressed in each question were aligned with concepts outlined by Bowling *et al.* (2008) and the addressed aspects if the study (macro/micro/symbolic and ontological). The method of analysis has been described in the previous chapter. Students selected to be interviewed were student 8, 15, 16, 20 and 22.

Table 4.3:

Summary of Misconceptions Identified from Interview 1

Question	Links to Macro/Micro/Symbolic and ontological aspects	**Student 8**	**Student 15**	**Student 16**	**Student 20**	**Student 22**
Define DNA.	DNA ontology	- DNA and gene are equivalent - DNA codes for traits	Student cannot define DNA	-	-	Student defines DNA as genetic code
Define chromosomes.	chromosome ontology	student defines chromosomes in context of DNA but not in context of genes	student defines chromosomes in context of chromatin but not in context of genes	Student cannot define chromosome	student defines chromosomes in context of DNA but not in context of genes	
Define genes.	gene ontology	student cannot define gene	Student defines gene as a trait	-	student cannot define gene	student cannot define gene
If You're Given a "Super Microscope" and You're Told to Find a Gene, Where Would You "Zoom In" and How Would You Know if It Is A Gene or Not?	gene ontology	Student cannot differentiate between gene and DNA	Student cannot differentiate between gene and DNA	-Student cannot differentiate between gene and DNA - Students thinks DNA and gene are separate	Student cannot differentiate between gene and DNA	Student cannot differentiate between gene and DNA
Do All Cells Carry the Same Genes?	link micro (genes) to micro (cells)	Student thinks differentiation arises because different cells carry different genes rather than all cells carry all genes but not all are expressed all the time	-	Student thinks differentiation arises because different cells carry different genes rather than all cells carry all genes but not all are expressed all the time	Cells do not carry the same genes	
What is genetic material made up of?	DNA and gene ontology	-	Assumes genetic material is made up of genes only	-	-	Assumes genetic material is made up of genes only
How Do We Look Like Our Parents? Why do we look	- link micro (genes) to macro (individual)	-Student confuses 23rd sex chromosome with the	- does not know how or why siblings looks different	-Student confuses 23rd sex chromosome with the	- does not identify role of meiosis in variation	-

different from our parents?		concept of sex cell that carries heritable material - does not identify role of meiosis in variation	- does not identify role of meiosis in variation	concept of sex cell that carries heritable material --does not identify role of meiosis in variation		
Put DNA, gene, and chromosome in a sentence.	- ontology of genes, DNA and chromosomes.	Student confuses between gene and DNA as units of information	Student identifies DNA as structural component of chromosomes and genes but does not relate chromosomes and genes	Student confuses between gene and DNA as units of information	- student does not link between gene and DNA	- student assumes DNA and gene are equivalent

Summary of the Results of Analyzing Interview 1. The main misconceptions identified were related to the nature of genes, DNA and chromosomes and related to patterns of inheritance. The students interviewed expressed a range of understandings demonstrated when answering the questions, however, there seems to be a consistency with the topics that students seem to struggle with relating the terms "gene", "chromosome" and "DNA". Furthermore, all the students struggled when describing "why we end up looking like our parents but different than our siblings", however only one student out of the five mentioned meiosis in his explanation, which is a key concept in when addressing the question. His answer was also the most accurate of the five:

> *Student 22:* Because our genetic code is not made up, it's passed down from our parents, some traits are more dominant than the others, that's why we have somethings from our mother or father, rather than being like one of them.
>
> *Teacher:* And though you have the same parents, how come you and your siblings look different?
>
> *Student 22:* Because we know in meiosis, we have a process in which it changes some genes between the chromosomes so they're not all the same, that's why there's a relevant difference

Furthermore, all the students were not able to differentiate between gene and DNA when asked to point out "a gene" using a "super microscope". This was somewhat of a tricky question because technically genes are made up of DNA, yet they are distinguished from DNA because they code for a particular protein while not all DNA codes for proteins. In summary, students struggled with the ontology of the gene concept and relevant topics (DNA and chromosome) which was also demonstrated in the GLAI test and two-tier questionnaire. Furthermore, the difficulty that the students faced when describing the microscopic processes involved in making off-springs look like their parents reflects a challenge in linking macro

aspects (appearance/traits) to microscopic aspect (genes and DNA related processes). In particular, the fact that four out of the five students did not mention meiosis as a significant microscopic process indicates that meiosis is not understood in context of genes properly. This was also shown in the two-tier questionnaire when students failed to link the black-box analogy to the process of meiosis.

Extended Response Questions. Extended response questions (ERQs) were administered throughout the study. The first ERQ was administered prior to the study to check for the students' understanding regarding a fundamental concept in genetics which is gene expression.

For this section, a question was administered prior to the study, and all students responded to the question. Students were asked, "How does a gene for a particular trait cause that trait happen? For example, how does a gene for dimples make the individual end up having them?". The question required students to identify the processes of protein synthesis, transcription and translation, as part of gene expression to lead to a particular trait. This involved the students making a connection between the micro and the macro and addressing the ontology of a gene in regard to its function. The method of analyzing the responses was outlined in the previous chapter. **Table 4.4** shows the student responses and identified misconceptions, whilst **Table 4.5** shows the summary of identified misconceptions and their frequency.

Table 4.4

Sample Student Responses to ERQ 1 and Identified Misconceptions.

Student	Response		Identified Misconceptions
#9	It all depends on the trait. If the trait was dominant then the person would have a higher chance of getting them, but recessive trait has a lower chance. Let's say that dimples are a dominant trait for one parent and the other parent has no dimples, there would be a 100 percent chance that one of their children would have dimples, but if it was recessive then it all depends on both parents. If both parents had dimples as a recessive trait then one of their children would have dimples.	1.	Assuming that if one of the parents expresses a dominant trait then the offspring will definitely inherit and express it as well
		2.	Gene expression no addressed, student most likely mixed up transmission with expression
#11	The gene gets activated and when it is activated it makes the changes that happen in your body. So, once it is activated the change and it then starts to get to the body.	3.	Assuming gene expression is about activating the genes without the mention of protein synthesis
#21	It depends on the alleles or whatever they are called, I forget what they were called. I know that if the father for example is recessive and the mother is dominant, the baby is born will get his mother's dimples. That is what I know from studying genetics last year	4.	Assuming that if one of the parents expresses a dominant trait then the offspring will definitely inherit and express it as well
		5.	Gene expression no addressed, student most likely mixed up transmission with expression
#14	In order for a gene to affect a person his parents must at least be recessive for this gene and if they're dominant that it would better. Then one of their children or more will carry that gene which in this case would be dimples.	6.	Mixing up concept of recessive and dominant
		7.	Gene expression no addressed, student most likely mixed up transmission with expression
#1	I do not know anything relating to this question.	-	

#23	A gene that codes for dimples would be present in the DNA of a person, and when the individual is growing up, the genome will be used as a blueprint for the body. So, there would be a mistake in the gene that codes for the muscles of the cheek where the body will not put a small piece of muscle there, which will result in a dimple forming. So, there is a mistake in the blueprint and so it shows as the body creates the muscles in the genome.	8.	Assumes gene expression takes place after birth
#6	A gene for a particular trait occurs in multiple ways. First of all, if the trait is dominant then you need to have on allele to be the dominant gene to have the trait. For example, if you have BB or Bb then you will have the trait and it doesn't matter which alleles you have if it is one of the two. If you have a Recessive trait then there is only one possible way to have the trait and that is to have bb. No other way you can have the trait, but you can be a carrier for the trait when you have Bb.	9. 10.	Assuming that if one of the parents expresses a dominant trait then the offspring will definitely inherit and express it as well Gene expression no addressed, student most likely mixed up transmission with expression
#4	To be quite honest I am not sure about this answer, my only answer would be that it was a coincidence or from god, and to make it more sure it would be whether or not the trait is dominant or recessive, if it was both dominant that would mean that the gene would be shown.	11.	Assuming expression of certain traits are merely coincidental
#12	As I am not sure, I can only guess that the dominant allele or trait would appear. So, for example if dimples were a dominant trait, the person would show them. If dimples were recessive, it would take the person to have two recessive traits, so that he could show them, or express them. So, it all depends on the trait being dominant or recessive. That is all I know about the process.	12. 13.	Assuming that if one of the parents expresses a dominant trait then the offspring will definitely inherit and express it as well Gene expression no addressed, student most likely mixed up transmission with expression

#20	Having the gene for dimples doesn't always mean that's it's going to be expressed. You might have the gene but not be expressed however it can be expressed by the offspring. If it was recessive, they should have two recessive alleles to be able to express it. If it was dominant, then it should have at least one dominant allele to express it. This can also be passed down from generation to generation.	14.	Mention of offspring indicates that students are referring to transmission

Table 4.5
Summary of Identified Misconceptions in ERQ 1.

ERQ Sequence	Question	Correctly Identified Conception	Frequency	Identified Misconception	Frequency
1	How does a gene for a particular trait actually make that trait happen? For example, how does a gene for dimples make the individual end up having them.	Identification of the processes of protein synthesis, transcription and translation, as part of gene expression.	4/23	Confusion of gene expression with gene transmission	13/23
				If a trait is dominant, then it will definitely be transmitted from parent to off-spring and then expressed in off-spring	3/23
				Genes code for a particular trait by directly causing it to happen; no mention of proteins	2/23
				Genes that determine physical features are randomly switched on/off throughout an individual's life	1/23

Summary of the Results of Analyzing the Extended Response Question. When asked how a gene is expressed most students answered the question incorrectly. Most students discussed modes of transmission from parent to off-spring rather gene expression within the organism. The most common misconception found in the student responses was the confusion between gene expression (the topic of the question) and gene transmission; these are two genetic concepts that do not directly relate. Many students, when discussing gene transmission, made the incorrect assumption that if the trait is dominant, then it will definitely be passed down from parent to off-spring, which is untrue.

Several students who answered the question correctly were able to identify the role of protein synthesis in gene expression. A few students went into detail to explain gene expression in context of the example (dimples) which was not required. Of those students, one made the wrong assumption when describing the timing of genetic expression. Student 23 incorrectly assumed that gene expression occurs while "growing up" rather than starts from conception. This misconception was also shown in the GLAI results. Because of the majority of students answering the question incorrectly, it was difficult to detect the misconceptions relating to the target conception. This common mistake reflects the difficulty students face in understanding the microscopic processes related to genetics by confusing transmission and expression.

Summary of Misconceptions Identified in the Pretests, Semi-Structured Interviews and Extended Response Questions. Errors on the GLAI indicated that students held misconceptions regarding the nature and role of mutations and how genes are expressed into traits. Regarding mutations, many students did not understand how mutations are inherited, nor the role they play in promoting variation. Regarding gene expression, many students held the misconception that one gene codes for one trait at all times, disregarding the role of the environment and the possibility for multiple genes to control a single trait. In the

two-tier questionnaire, students did not perform well on the item that required them to describe a gene, interpret a model describing meiosis, and determine patterns of inheritance using a pedigree. In the ERQ's, students struggled to describe how a gene is expressed, and instead described process of gene transmission from parent to off-spring. Questions from the semi-structured interviews revealed that students struggled with defining the concept of gene in context of other genetic-related concepts and struggled to describe modes of inheritance when asked "why do we look like our parents/why do we look different than our siblings". **Table 4.6** summarizes the conceptions from the GLAI, the two-tier questionnaire, the first SSI and the ERQ 1 that the students seemed to struggle with (adapted from Bowling *et al.* (2008)), along with the identified misconceptions.

Table 4.6

Summary of Challenging Conceptions and Misconceptions Identified from the pretests, SSI-1 and ERQ-1

Tools	**Challenging Conception**		**Links to Macro/Micro/Symbolic and ontological aspects**		**Misconceptions Identified**	
GLAI	15.	**Ib.** Occasional errors in DNA structure and replication result in genetic variation.	17. 18.	Link micro to macro Ontology of genes	1.	Mutations in one cell can influence the whole multicellular organism
					2.	Mutations have no role in romoting genetic variation
	16.	**IIIc.** Most human traits, including diseases, result from the products of multiple genes interacting with environmental variables: examples include height, heart disease, cancer, and bipolar disorder.			3.	Presence of a mutation coding for a disease in the genome indicates that this disease will definitelt be expressed in the organism
					4.	Mutations produce new genes/ chromosomes /enzymes /cells for the organism
					5.	the environment plays the largest role in actualizing a trait
					6.	most traits are determined heavily by genetics with the environment having little effect on complex traits.
					7.	The environment plays a major role in determining complex traits
Two-Tier Questionnaire	**8.**	**IIa.** Chromosome number is reduced by half during meiosis, which results in the formation of genetically different gametes.	11. 12.	Linking macro to micro Ontology of genes	13.	Different combinations of chromosomes are responsible for the different cells and function in the body
					14.	Cells divide to form different cells with varying chromosome number to fulfill different functions
	9.	**Ic.** DNA is organized into cellular structures called			15.	Genes are the smallest unit of structure in a chromosome.

		chromosomes. Genes are segments of' DNA within chromosomes.		16. Genes are a segment in a DNA molecule. 17. If both a female and male are affected by a disease, then it must be autosomal
	10.	**IIb.** Understanding Mendelian patterns of inheritance, and their biological basis, allows probability statements about the occurrence of traits in offspring.		18. If the parents are normal but one of the offspring is affected, then the disease is definitely autosomal recessive 19. To check whether an organism is heterozygous or homozygous dominant, crossing with another homozygous dominant will yield observable results 20. To check whether an organism is heterozygous or homozygous dominant, crossing with another 21. heterozygous will yield observable results
SSI-1	**22.**	**IIb.** Understanding Mendelian patterns of inheritance, and their biological basis, allows probability statements about the occurrence of traits in offspring.	25. Ontology of genes, DNA and chromosomes 26. Relating micro to macro	27. Confusion between the concept of the 23rd sex chromosome which carries the sex-linked genes with the concept of sex cell that carries heritable material that will be used in fertilization 28. Whether a trait will be expressed in the off-spring or not, it is determinant on whether it is dominant or recessive when carried by the parents 29. Meiosis does not play a role in the degree of resemblance between parents and offspring **30.** Meiosis does not play a role in variation between siblings
	23.	**Ic.** DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.		
	24.	**IIIa.** Many genes code for proteins, which in turn produce individual traits.		

ERQ-1	**31.**	**IIIa.** Many genes code for proteins, which in turn produce individual traits.	32. Linking micro and the macro 33. Ontology of genes	**34.**	Confusion between gene expression and gene transmission
				35.	Whether a trait will be expressed in the off-spring or not, it is determinant on whether it is dominant or recessive when carried by the parents

When students were asked to respond questions relating to patterns of inheritance directly (on the GLAI and Two-tier), many of them were able to answer those questions correctly. These questions that most students solved correctly involved alleles and the use of a Punnett squares to predict patterns of inheritance. This shows that students are comfortable using these symbols to answer direct questions regarding predicting the outcome of a particular trait. However, when students were asked to describe the process (microscopic), such as in the interview questions and extended response questions, students faced difficulty in responding. Meaning that even though students can address questions that require them to manipulate symbols that represent a particular microscopic phenomenon, they are not able to recognize and/or describe this microscopic phenomenon. The students might be able to identify the microscopic concept but are challenged when asked to link it to its symbolic representation. For example, in the GLAI, most students were able to answer the question asking them to predict the probability of an off-spring inheriting Cystic Fibrosis (no.29 on the GLAI), but were not able to describe why we look like our parents, even though both question address the concept of meiosis. The GLAI question involves the use of simple Punnett square to predict the probabilities. The Punnett square is a summary of all possible outcomes from both meiotic divisions of the parents and the different combinations that can be produced accordingly. Not understanding the link between the Punnett square and meiosis and how they address the concept of gene transmission is problematic. This reflects the ability of students to link the symbolic to the macro, but challenges in linking the micro to the macro.

In summary, student misconceptions can be categorized under two headlines, the "ontological", which encompasses student difficult in defining and understanding the nature of a gene and "multi-representational", where the students struggled to connect symbolic

representations to the microscopic representations they describe. The following section will describe the evolution of the students' conceptions throughout the study's progress

Change of Student Conceptions Throughout the Study

In the previous section, the first research question was addressed by identifying student misconceptions through the pretests (the GLAI and the two-tier), the extended response question and the interview done prior to the study. These questions were used to identify students' genetics conceptions and identify how these conceptions related to multiple representations and ontology. In this section, the second research question regarding how the students' conceptions were influenced by the study will be addressed by comparing the misconceptions identified in the first section to the misconceptions identified throughout the duration of the study.

This section will include misconceptions identified from the consecutive two GLAI tests administered, one done during the third week of the study and one done after the study, one two-tier questionnaire done after the study, four ERQ's done weekly as the study progressed, four interviews done throughout the study and twenty-three total class lessons. Data from the class lessons include the videotaped and transcribed lessons, student work (including the Project referenced in chapter 3) and the teacher reflection.

The GLAI. As mentioned in the previous section, the GLAI was administered a total of three times. During the first GLAI, all participants completed the test, during the second GLAI Test, twenty out of the twenty-three participants completed the test, and on the third GLAI, only fifteen of the twenty-three participants took the test. Out of the twenty-three participants only thirteen students completed all three GLAI tests. This discrepancy in participation made it slightly challenging to compare the performance on all three tests. To compensate for this discrepancy, the results of the thirteen students are described in Table 4.7. Identified misconceptions, related concept (in accordance with concepts set by Bowling

et al., 2008) and study related aspect (links to Macro/Micro/Symbolic and Ontological aspects) have already been made per question in the previous section (Table 4.6).

Table 4.7

Performance per item of the thirteen students who did all three GLAI Tests

Question		Frequency of students who answered correctly on the First GLAI	Frequency of students who answered correctly on the Second GLAI	Frequency of students who answered correctly on the Third GLAI	Related concept (in accordance with concepts set by Bowling *et al*., 2008)	Study Related Aspect (links to Macro/Micro/Symbolic and Ontological aspects)
1.	What is the relationship among genes, DNA, and chromosomes?	8	9	7	**Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.**	2. Microscopic 3. Ontology of the terms in regard to how they relate
4.	Adult height in humans is partially determined by our genes. When environmental conditions are held constant, humans have a wide variety of heights (not just short, medium, and tall). Height is probably influenced by:	6	10	6	**IIIc. Most human traits, including diseases, result from the products of multiple genes interacting with environmental variables: examples include height, heart disease, cancer, and bipolar disorder.**	-relating macroscopic (height) to micro (gene)
5.	Our understanding of how genes function indicates that:	7	7	6	**IIIa. Many genes code for proteins, which in turn produce individual traits.**	-microscopic (gene) - ontology of gene (function)
6.	What is the most likely way the genetic system (genetic material and the genetic code) of living organisms evolved?	3	4	2	**Ia. DNA is the genetic material of virtually all different types of organisms.**	7. Linking micro (genetic code) to macro (evolution/ differences between species) 8. Ontology of genetic code
9.	Which of the following is INCORRECT regarding meiosis?	9	6	9	**IIa. Chromosome number is reduced by half during meiosis, which results in the formation of genetically different gametes.**	10. Micro (meiosis) 11. Link micro (meiosis) to micro (cell) 12. Link micro (meiosis) to macro (organism) 13. Ontology of meiosis
14.	Sometimes a trait seems to disappear in a family and then reappear in later generations. If neither parent has the trait, but some of the offspring do, what would you conclude about the inheritance of the trait?	9	8	6	**IIb. Understanding Mendelian patterns of inheritance, and their biological basis, allows probability statements about the occurrence of traits in offspring**	15. Link micro (gene) to macro (organism) 16. Ontology of a gene
17.	An individual is found to have a mutation in a gene associated with breast cancer. In which cells is this	3	2	3	**Id. virtually all cells within an individual contain the same genetic constitution- Different cells and tissues are produced through differential gene activity.**	18. Link micro (mutation) to micro (cells) 19. Link micro (mutation) to macro (organism)

	form of the gene located?						
20.	Mutations in DNA occur in the genomes of most organisms, including humans. What is the most important result of these mutations?	3	2	3	**Ib. Occasional errors in DNA structure and replication result in genetic variation.**	21. 22.	Link micro (mutation) to micro (gene/ enzyme/ chromosome/ cells) Link micro (mutation) to macro (organism)
23.	Multiple genes are associated with complex diseases such as cancer and mental disorders. When an individual is tested for these genes, what do the results indicate?	6	7	4	**IVb. There are other genetic variations that result in disease less consistently, for example, the BRCA1 mutation associated with breast cancer.**	Link micro (genes) to macro (disorder)	
24.	Which of the following is a current benefit of the application of genetics and genetic technology to health care?	10	6	5	**VIa. The current and future application of genetics and genetic technology to such areas as health care, forensic analysis, genetically modified organisms, etc. holds great potential for improving life.**	Link micro (genes/genetic code) to macro (organism/society)	
25.	A woman has been told she carries a mutation associated with breast cancer. How does this influence her likelihood of developing breast cancer?	7	7	7	**IVb. There are other genetic variations that result in disease less consistently, for example, the BRCA1 mutation associated with breast cancer.**	26.	Link micro (mutation) to macro (organism)
27.	Many geneticists study the genetic material of organisms such as mice, fruit flies, and yeast. They are able to apply what they learn from these organisms to humans because virtually all different types of organisms:	8	5	5	**Ia. DNA is the genetic material of virtually all different types of organisms.**	28. 29.	Link micro (genetic code) to macro (organism) Ontology of genetic code
30.	As HIV has spread around the world, we know some individuals are resistant to the effects of the virus even though they are HIV positive. Why?	9	2	5	**Va. Genetic variation is the rule rather than the exception in the living world and is the basis for evolution by natural selection: without genetic variation there can be no differential selection, and no survival of any species.**	31.	Link micro (genetic differences) to macro (organism/ resistance)
32.	Which of the following is a characteristic of mutations in DNA?	1	3	3	**Ib. Occasional errors in DNA structure and replication result in genetic variation.**	33. 34. 35.	Micro (mutations) Ontology of mutations Link micro (mutation) to macro (organism)
36.	What is the relationship between DNA and chromosomes in higher organisms?	9	10	8	**Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes.**	37. 38. 39.	Microscopic (DNA, chromosomes) Link micro (DNA, chromosomes) to macro (organisms) Ontology of genes in context of DNA and chromosomes

40.	Huntington's disease is a genetic disorder caused by a dominant gene. Symptoms begin in adulthood and the disease is ultimately fatal. What is an ethical dilemma presented by Huntington's disease when a parent is diagnosed with the disease?	7	5	5	**VIb. Like all technologies, genetic technologies are fallible and have unintended consequences, some of which can be harmful to individuals, families. or groups.**	Link Micro(genes) to macro (organism, society)	
41.	Regarding complex traits such as IQ, lung cancer, prostate cancer, etc., how do geneticists describe the contributions of ones' genetic makeup and the environment?	2	4	4	**IIIc. Most human traits, including diseases, result from the products of multiple genes interacting with environmental variables: examples include height, heart disease, cancer, and bipolar disorder.**	42.	Link micro (genes) to macro (trait, organism)
43.	How is the expression of genes regulated or controlled?	3	7	6	**IVc. Much of gene regulation involves turning genes on and off at the right time.**	Ontology of genes	
44.	If an individual has a genetic test for a mutation causing a particular disease, and the result is positive, what will that most likely mean?	5	7	6	**IVa. Some genetic variation results in disease in virtually every environment, for example, the mutations associated with Huntington disease, Tay-Sachs disease, and cystic fibrosis.**	45. 46.	Link micro (mutation) to macro (organism) Ontology of mutations
47.	What effect, if any, does an individual's environment have on the development of his or her traits?	4	4	3	**IIIb. The functions of a gene and its protein product can be affected by the environment at one or many steps involved in producing a given trait.**	48. 49. 50.	Link micro (gene) to macro (organism) Link macro (environment) to macro (organism) Link macro (environment) to micro (gene)
51.	Your muscle cells, nerve cells, and skin cells have different functions because each kind of cell:	9	6	7	**Id. virtually all cells within an individual contain the same genetic constitution- Different cells and tissues are produced through differential gene activity.**	52.	Link micro (gene) to micro (cells)
53.	At what times during an individual's life does the environment influence the expression of his or her genes?	0	3	1	**IIIb. The functions of a gene and its protein product can be affected by the environment at one or many steps involved in producing a given trait.**	54. 55.	Link macro (environment) to micro (gene) Link macro (environment) to macro (organism)
56.	Which of the following is INCORRECT regarding the genetic differences among ethnic groups?	1	1	3	**Vb. Genetic variation is much greater within traditional human ethnic groups than among them. Superficial phenotypic differences do not reflect the high degree of genetic relatedness among traditional ethnic groups**	57.	Link micro (DNA sequence) to macro (organisms)
58.	What is the relationship between genes and traits expressed in individuals?	7	6	5	**IIIa. Many genes code for proteins, which in turn produce individual traits.**	59.	Link micro (genes) to macro (traits of an organism)

60.	Which of the following does NOT accurately reflect Charles Darwin's basic principles of evolution?	8	2	4	**Va. Genetic variation is the rule rather than the exception in the living world and is the basis for evolution by natural selection: without genetic variation there can be no differential selection, and no survival of any species.**	61.	Link micro (genetics) to macro (organisms)
62.	Which of the following is NOT considered an ethical or legal concern?	2	2	3	**VIc. Science often can tell us what we can or cannot do, but it does not always indicate clearly what we should do. Those decisions arise from the intersection of science with ethics, the law. and public policy.**	63.	Link micro (genetics) to macro (organisms/society)
64.	Cystic fibrosis (CF) is a recessive disorder, meaning that an individual must have two copies of an abnormal CF gene to be affected. What is the probability that a child of two individuals who each have one copy of the abnormal gene will be affected with CF?	8	10	6	**IIb. Understanding Mendelian patterns of inheritance, and their biological basis, allows probability statements about the occurrence of traits in offspring.**	65.	Link micro (gene/mutation) to macro (trait/organism)
66.	Which of the following is a correct statement about science and the scientific method?	9	9	5	**VIc. Science often can tell us what we can or cannot do, but it does not always indicate clearly what we should do. Those decisions arise from the intersection of science with ethics, the law. and public policy.**	-	
67.	The muscle cells of humans contain 46 chromosomes. How many chromosomes do unfertilized human egg cells contain?	10	11	9	**IIa. Chromosome number is reduced by half during meiosis, which results in the formation of genetically different gametes.**	68.	Link micro (chromosome) to micro (sex cell)
69.	What is an example of an unexpected consequence when current genetic technologies are used?	4	1	1	**VIb. Like all technologies, genetic technologies are fallible and have unintended consequences, some of which can be harmful to individuals, families. or groups.**	70.	Link micro (genetics) to macro (organisms)

The GLAI Analysis. It is important to note that the third GLAI was administered while the students were quarantined. Furthermore, as mentioned in the previous section, out of the thirty questions, question numbers 23, 25, 26 and 30 discussed concepts that were unfamiliar (not directly relevant to the content of genetics in IB) to the students such as ethnicities (23), evolution (25), ethical and legal concerns (26) and genetic technology (30), and hence will not be regarded with importance as other items that are more familiar to the students and were addressed in the lessons.

In general, as the study progressed, it is expected that students perform increasingly better on the GLAI, however, looking at Table 4.7, this was not seen on any of the items on the three GLAI tests. Instead, the students' performance seemed to improve on the second GLAI test then decline on the third for most of the items. This included item, 1, 2, 4, 9, 15, 18,19, 22, 27 and 29, which accounted for one third of the items. This can be explained by the fact that the third GLAI was done during the quarantine period, where they had two weeks of no work, then one week with lessons on the remaining sections, and hence some of the information might not have been retained during that time. Furthermore, students were aware that their grades are secure, as explained under the context section, and hence this might have influenced their motivation. For the remaining items, students' performance increased at the second GLAI then increased again on the third for six items (5, 7, 8, 13, and 25), consistently declined for three out of the thirty items (6, 10, and 24), and showed a variation of inconsistent patterns on the remaining items.

When analyzing the items that the thirteen students performed most poorly on and comparing it to the whole class's performance on the first GLAI, consistencies in the nature of challenging concepts can be detected. In the first GLAI done by the whole class (analyzed in the previous section) and through this comparative table targeting the performance of the thirteen students (table 4.7) the items that students did the poorest on are the same. Across all three GLAI tests for the thirteen students, and on the first GLAI test results of the class, the students consistently were challenged by questions relating to mutations (item 7 and 14) and relating genes to the environment (items 17, 20, 22). There has been little to no improvement in student performance on these items throughout the study indicating that the instruction might not have targeted these misconceptions properly.

To further analyze the performance of the students on the GLAI tests, the scores of the thirteen students who participated in all the three GLAI tests are displayed in Table 4.8.

Table 4.8
Student Scores on the three GLAI Tests

Student (Identified by Number)	Score on GLAI 1 (out of 30 points)	Score on GLAI 2 (out of 30 points)	Score on GLAI 3 (out of 30 points)
2	21	14	13
6	13	13	5
7	15	12	6
10	14	10	12
11	13	11	8
12	5	7	8
13	15	10	5
14	8	10	8
15	16	21	19
19	14	7	8
20	18	19	20
21	5	9	6
22	20	22	23

From the performance on the items from Table 4.7, one can predict that the students' scores were not too well on the third GLAI test and should be highest on the second. The highest scores of the students out of the three were highlighted in green, and the lowest were highlighted in red. Out of the thirteen students who did all the three GLAI tests, most did best on the first test. Five students performed most poorly on the first GLAI, five on the third, two students performed worst on the second GLAI and one student performed equally on the first and third. The student result on the three GLAI tests indicate that there was no significant improvement throughout the study.

The Two-Tier Questionnaire. As mentioned in the previous section, the two-tier was administered a total of two times; once before and once after the study. In this section, the results from the second two-tier will be compared to the first to analyze how conceptions

have changed along the study. Table 4.9 summarizes the results on the two-tier questionnaires taken before and after the study. As mentioned before, twenty-three did the first students and only fifteen did the second. To accurately compare the performance, only the results of the students who did both tests are shown in the table, it is important to point out that second two-tier was done online rather than in class given the situation (addressed earlier in the chapter)

Table 4.9

Performance per Item on the Two-Tier Questionnaire for the fifteen students that did both tests

Question	**Frequency of students who answered the item correctly on the first Two-Tier (out of 15)**	**Frequency of students who answered the item correctly on the second Two-Tier (out of 15)**	**Reasoning Type**	**Study Related Aspect per Item**	**Misconception held by the student**
Item 1, Tier 1: The trait, curly hair, is dominant to straight hair. If we use "C" to represent the dominant allele (gene) for curly hair and "c" for the recessive allele, would a person with genotype Cc have curly hair? Item 1, Tier 2: Reason for the above [Item 1, Tier 1]?	9	10	Cause-to-effect reasoning. Mapping genotype to phenotype	Linking Symbolic to Macro	Heterozygous genotype (Cc) does not express the dominant trait Dominant trait is only expressed in homozygous form 74. The person needs to have CC for curly hair. 75. The person may or may not have curly hair. 76. The recessive allele c is expressed.

Item 2, Tier 1: Which of the following best describes the trait in the following pedigree?	6	5	Effect-to-cause reasoning: Monohybrid inheritance: Mapping phenotype to genotype	77.	Linking Macro to Micro/Symbolic	78.	A dominant allele can be present in the parents, not show, and be passed down to off-spring and show
Item 2, Tier 2: Reason for the above:				79.		80.	The trait is recessive Only one of the three children in the second generation has the trait.
						81.	The trait is dominant because both the female in the first generation and her son have the trait.
						82.	The trait can be either recessive or dominant based on the pedigree.
Item 3, Tier 1: The following shows a “Black Box” that provides a simplified model to show a process in genetics. What does the “Black Box” represent?	4	2	Process reasoning: Punnett squares (input/output reasoning): Meiosis process (event reasoning) Mitosis process	83.	Linking symbolic and Micro	84.	The image shown to divide the cell into four cells with half the number of the original chromosome number represents fertilization
						85.	Represents a cell division that occurs after fertilization
Item 3, Tier 2: Reason for the above [Item 3, Tier 1]?				86.		87.	Different combinations of chromosomes are responsible for the

						different cells and function in the body
					88.	Cells divide to form different cells with varying chromosome number to fulfill different functions
Item 4, Tier 1: Which one of the following is the best description of a gene?	4	7	Process reasoning: Mapping information in DNA base sequence (genotype) to amino acid sequence in protein synthesis (phenotype)	89.	Ontology of a gene	90. Genes are the smallest unit of structure in a chromosome.
						91. Genes are a segment in a DNA molecule.
Item 4, Tier 2: Reason for the above [Item 4, Tier 1]?				92.		93. Genes are defined in regard to the structural role they play in composing chromosomes
						94. Genes are defined as being structurally made up of DNA
Item 5, Tier 1: The pedigree chart below shows the inheritance of a common genetic disease in Western Australia. Which of the following best describes the allele that gives rise to the trait?	3	2	Effect-to-cause reasoning: Monohybrid inheritance: Mapping phenotype to genotype	95.	Linking Macro to Micro/Symbolic	96. Disease is sex-linked dominant
						97. Disease is sex-linked recessive
						98. Disease is autosomal dominant

Item 5, Tier 2: Reason for the above [Item 5, Tier 1]?				99.	100. 101.	If both a female and male are affected by a disease, then it must be autosomal If the parents are normal but one of the offspring is affected, then the disease is definitely autosomal recessive
Item 6, Tier 1: Some dogs bark when following a scent, others are silent and are called silent trackers. Barking is dominant (allele B) to non-barking (allele b). A hunter owns a barker which he wants to use for breeding purposes. However, he wants to be sure it has a genotype of BB. What is the genotype of the bitch he should mate with this dog?	1	1	Cause-to-effect reasoning; Monohybrid inheritance: Mapping genotype to phenotype	102.	Linking Symbolic/Micro to Macro	103. 104.	To check whether an organism is heterozygous or homozygous dominant, crossing with another homozygous dominant will yield observable results To check whether an organism is heterozygous or homozygous dominant, crossing with another heterozygous will yield observable results

Item 6, Tier 2: Reason for the above [Item 6, Tier 1]?				105.		106. If no silent trackers appear in the offspring, he can be sure that his dog's genotype is BB. 107. - If the dog is Bb, the chances of getting silent trackers in the offspring are zero.
Item 7, Tier 1: Peter is an albino who was born without the ability to make a pigment in the skin. Albinism is a recessive characteristic. Suppose we use "A" for the dominant gene (allele) and "a" for the recessive gene, what would be Peter's genotypes (genes) for albinism?	6	5	Effect-to-cause reasoning: Mapping phenotype to genotype	108.	Linking Macro to Symbolic	109. Recessive traits can be expressed in heterozygous form
Item 7, Tier 2: Reason for the above [Item 7, Tier 1]?				110.		111. Having one copy of recessive allele is enough to express recessive trait 112. In heterozygous form, the recessive allele is expressed

Two Tier Analysis. It is expected that students perform better on the second Two tier that on the first, since it is after the instruction. However, this only applied to two items on the test which was Item 1 and Item 4. Item 4, "Which one of the following is the best description of a gene?" had the most significant change in performance where three more students answered the item correctly on the second compared to the first. Interestingly, this was one of the items that the class did poorly on the first two-tier questionnaire. This might indicate that the students' understanding of the ontology of gene has improved throughout the study.

Of the remaining five items, students performed worse on the second two-tier items and the same performance on both for one item (item 6). As mentioned in the last section, Item 6 was challenging because 2 of the options on the second tier were correct with one being more accurate than the other. Ten students out of the fifteen chose the less accurate option and hence did not score the item.

When compared to the class's results on the first tier, where students did most poorly on items 3,4,5 and 6, the students still did poorly on items 3 and 5. On Item 3, which addresses the role of meiosis in producing four genetically different cells through the use of the "black-box analogy" which relates the symbolic aspect to the micro aspect, there was a decrease in performance within the group of students that did both tests. This shows that students still struggled with the concept of meiosis and using analogies to describe the purpose of the process. It is important note that item 3 addresses the highest level of reasoning on the two-tier questionnaire, Level VI which involves, process reasoning: Punnett squares (input/output reasoning): Meiosis process (event reasoning) and Mitosis process. Item 5, which as mentioned in the last section, has two somewhat accurate answers was also an item that students did poorly on.

To further analyze the performance of the students, the scores of the students who did both questionnaires have been summarized in Table 4.10.

Table 4.10

Two Tier Scores of the students who did both Questionnaires.

Student	Score on Two-Tier 1 (out of seven points)	Score on Two-Tier 2 (out of seven points)
2	4	6
4	2	0
6	4	1
7	3	4
8	2	2
10	0	3
11	2	2
12	3	2
13	3	0
14	1	1
17	2	1
19	0	0
20	3	4
21	0	0
22	4	6

Out of the fifteen students, five students' scores improved, five decreased and five remained the same. Th net difference in scores is not a significant indicator of change in conceptions.

Interviews. As mentioned in the previous section, semi-structured interviews were administered before, during and after the study, a total of four times. As indicated in Chapter

3, five students were consistently interviewed throughout the study. In this section, the remaining interviews are analyzed to identify student misconceptions and are compared with each other to identify any changes in conception. As in the previous section, students selected to be interviewed were student 8, 15, 16, 20 and 22. It is important to point out that the last two interviews were done online rather than face to face given the situation (addressed earlier in the chapter). Furthermore, all students took part of all the interviews except for student 8 who missed the second interview and student 20 who missed the last interview.

Similar to how the first interview was analyzed in section one, the remaining interviews were also analyzed with the aid of a peer teacher to increase the reliability of the analysis. The details of this process where addressed in chapter 3. Table 4.11 summarizes the conceptions identified from the four interviews. It is important that the frequencies/numbers on Table 4.11 are for the five students, hence whatever number listed is out of five, except in interview 2 and interview 4 where the frequency is out of 4 students not five because one student missed on it.

Table 4.11

Frequency of Conceptions Identified in the four Interviews for the five Students

Interview set	**Question**	**Targeted Conception (out of five)**		**Detected Misconception (out of five)**	
1	define DNA.	DNA is a type of nucleic acid (macromolecule) that makes up the genetic material	2	Student cannot define DNA	1
				Student defines DNA as genetic code	1
				DNA and gene are equivalent	1
				DNA codes for traits	1
	define chromosomes.	113. Are made up of condensed DNA and carry genes	1	Student cannot define chromosome	1
				student defines chromosomes in context of chromatin but not in context of genes	1
				student defines chromosomes in context of DNA but not in context of genes	2
	define genes.	114. Made up of DNA 115. Code for proteins 116. Act as instructions of the cell	1	Student cannot define gene.	3
				Student defines gene as a trait.	1
	If you're given a super microscope and you're told to find a gene, where would you zoom in and how would you know if it is a gene or not	- what differentiates a gene from other DNA segments is the functional role of a gene in coding for proteins	0	Student cannot differentiate between gene and DNA	5
	Do all cells carry the same genes?	all cells carry the same genes	2	Student thinks differentiation arises because different cells carry different genes rather	2

			than all cells carry all genes but not all are expressed all the time
			Cells carry different genes 1
What is genetic material made up of?	genetic material is made up of genes and non-coding sequences	3	Assumes genetic material is made up of genes only 2
How do we look like our parents, and how come we differ from our siblings?	- our genetic material is made up of 50% maternal and 50% paternal chromosomes	1	-Student confuses 23rd sex chromosome with the concept of sex cell that carries heritable material 2
	- how much we look like either parent is determined by what genes were inherited from each parent, and the interaction of those inherited genes		- does not identify role of meiosis in variation 4
			- does not know how or why siblings looks different 1
Put DNA, gene, and chromosome in a sentence.	-Structurally, the genetic material is made up of DNA		Student confuses between gene and DNA as units of information 2
	- Genetic material is divided into chromosomes		Student identifies DNA as structural component of chromosomes and genes but does not relate chromosomes and genes 1
	-different chromosomes carry different genes		- student does not link between gene and DNA 1
			student assumes DNA and gene are equivalent 1

2	Differentiate between chromosomes, sister chromatids, homologous chromosomes ad chromatin. What do they describe, and can DNA be two of those at the same time?	117. 118. 119. 120.	Sister chromatids are a result of when chromosomes are replicated before cell division Homologous chromosomes are chromosomes that carry the same genes and inherited from each parent. Chromatin is the uncondensed DNA that exists when the cell is not preparing to divide. During prophase 1 of meiosis sister chromatids and homologous chromosomes can be identified.	1	Describes them as different stages of DNA that cannot coexist 121.	3 122.
	Differentiate between allele and gene, and how can you differentiate them on a DNA strand.	- alleles are different forms of a gene - alleles of the same gene differ in a few bases - alleles don't physically exist	2 1	Student cannot recognize the physical differences between alleles of the same gene	1

	How does a cell read a gene?	-involves process of transcription and translation	3		Through the activation or deactivation of genes but no details on how	1	
	Distinguish between DNA and gene	DNA is a physical strand of nucleotides whereas genes are DNA that code for a trait	2		Student cannot determine how to distinguish DNA from gene	2	
3	What is the difference between genotype and phenotype?	123. Genotype is the allele combination carried by the individual's genes 124. Phenotype is the product of this allele combination manifested through gene expression/protein synthesis	2	125. 126. 127.	Defined genotype as "letters' (allele symbols) Defines genotype as outcome of genes Challenged in distinguishing both, confused both terms	1 2 1	
	What is the difference between a chromosomal disorder and a genetic mutation? How do they compare in regard to modes of inheritance?	128. Chromosomal disorders arise due to failure of chromosomes to divide during the meiosis of either parents 129. Genetic mutations/disorders are a result of the inheritance of	130.	131.	Inheritance plays no role in genetic mutations. It is merely an error in transcription and translation. (source not discussed)	4	

		a mutated gene from either parent		132. Inheritance plays a role but no mention of meiosis, gametes or mutation in the gamete cells	1
	how is the sex of the offspring determined?	- sex of the off-spring is determined by the inheritance of particular sex chromosomes from parents - this is random depending which gamete joins with which gamete resulting in what twenty-third chromosomal combination	5		
	Why do we look like our parents, what processes that happen microscopically, make us look like our parents?	- our genetic material is made up of 50% maternal and 50% paternal chromosomes - how much we look like either parent is determined by what genes were inherited from each parent, and the interaction of those inherited genes	5		
4	Define DNA.	DNA is a type of nucleic acid (macromolecule) that makes up the genetic material	3	DNA codes for protein	1
	Define Chromosomes.	133. Are made up of condensed DNA 134. Carry genes	4	135. 137.	136. 138.

Define genes.	139.	Made up of DNA	142. 1	143.	Same as DNA	2
	140.	Code for proteins				
	141.	Act as instructions of the cell		144.	DNA codes for genes	1
What is meant by the genetic code being universal?	Codons, a set of three nucleotides, codes for the same amino acid across different species.		3	Genetic code is universal means that all genetic code is made up of DNA		1
How are traits expressed?	Transcription, translation		2	Different genes are expressed using different mechanisms		1
				Discusses gene transmission: inheritance/dominance		1
How are mutation passed inherited?	145.	Inheritance of a mutation is determined by what genes were inherited from each parent, and the interaction of those inherited genes	1	148.	Mutations happen in some cells only	1
	146.	The meiotic products from both parents combined should include the mutated genes				
	147.	Probability of such could be deduced from a Punnett square				
				149.	No clear indication of inheritance of mutation sequence from parents through meiosis then fertilization	2

Even though there seems to be improvement when distinguishing different genetics related concepts, there still seems to be a difficulty when slightly different concepts are compared or put in one context. This was particularly evident in interview three when students were asked to compare chromosomal disorders and genetic diseases. Most students failed to draw the similarity between the two in regard to inheritance and the role of meiosis and fertilization in both. Instead, students focused on each individually in the sense that chromosol abnormalities involved a physical error of failure to divide whereas mutations involve a "code" disorder where the information is changed. This indicated that students are challenged in linking microscopic processes together that lead to a macroscopic outcome (disease). This was also shown when students were asked "why/how we end up looking like our parents" students find it difficult to link meiosis of two different individuals to the outcome of the off-spring and there is a reoccurring mention of Punnett squares which indicates students find difficulty in linking this symbolic tool to the microscopic process it is related to (meiosis and fertilization).

Interview responses also showed a challenge in understanding the nature of mutations in general and how they are passed down and what it takes for a mutation to be expressed. Students seem to struggle with differentiating the concept of genetic disease and the concept of mutation. A genetic disease is caused by a mutation that has been passed down through the gametes, however a mutation does not always cause a genetic disease. In fact, mutations are almost always insignificant, and only matter when they occur on a coding sequence in a gamete. This was shown on both the third and the fourth interview. This challenged understanding can be linked to a challenge in understanding of the genetic code in a multi-cellular organism.

Extended Response Questions. As mentioned earlier, extended response questions (ERQs) were administered throughout the study. A total of four extended response questions

were administered, one before, two during, and one after the study. As with the GLAI and two-tier questionnaire there was a varying number of participants as the study progressed. All students participated in the first ERQ, twenty-one students participated in the second and in the third, and only eighteen participated in the last. It is important to point out that the last two extended response questions were done online rather than in class given the situation (addressed earlier in the chapter). Each ERQ addressed a particular set of conceptions and hence it might be challenging to directly compare the evolution of particular conceptions. However, this can be compensated by examining results from other instruments to create a more accurate comparison.

As mentioned in chapter 3, ERQ responses were analyzed with the aid of a peer teacher. The results of the analysis are summarized in table 4.12.

Table 4.12

ERQ Questions and frequency of identified student conceptions

ERQ Sequence	Question	Correctly Identified Conception	Frequency	Identified Misconception	Frequency
1	How does a gene for a particular trait actually make that trait happen? For example, how does a gene for dimples make the individual end up having them.	Identification of the processes of protein synthesis, transcription and translation, as part of gene expression.	4/23	Confusion of gene expression with gene transmission	13/23
				If a trait is dominant, then it will definitely be transmitted from parent to off-spring and then expressed in off-spring	3/23
				Genes code for a particular trait by directly causing it to happen; no mention of proteins	2/23
				Genes that determine physical features are randomly switched on/off throughout an individual's life	1/23
2	Each type of species has their distinct chromosome number. Humans have a chromosome number of 46,	Change in chromosome number within a species a result of an error in division in sex cells where the	5/21	Chromosomal abnormalities are equivalent to DNA abnormalities/mutations	3/21

	while chimpanzees have a number of 48. If I somehow managed to successfully add 2 pairs of chromosomes to a human stem cell so that it will have 48 chromosomes, what do you think will happen? will this cell develop into a chimpanzee cell? why or why not?	offspring ends up having one more or one less copy of a particular chromosome			
		Different species carry different genes particular to their species.	5/21	Changes of chromosome number introduces new traits/ traits from another species	4/21
		Organization of genes on chromosomes is not the same across species, and hence adding or removing chromosomes does not switch the organism from one species to another	9/21	Animal cells are flexible and can change to any type of animal cell by manipulating chromosome number	1/21
3	What is meant by the genetic code is universal? explain how the genetic code is universal.	Codons, a set of three nucleotides, codes for the same amino acid across	6/18	Stating the genetic code “is the same” with no further elaboration or explanation	6/18
				Genetic code is the same meaning they have the same nucleotides	3/18

		different species.		Mention codons without mentioning amino acids/proteins	2/18
4	In your own words, explain how Genetically Modified Organisms (GMOs) are produced, such as insulin producing bacteria.	The nature of genetic code, being universal, allows for the insertion and later expression of target genes in host cells.	0/18	Brief/Naïve description of the process of creating a GMO	7/18
		Correct sequence of steps involved in genetic engineering	7/18	Involves changing nucleotide bases	1/18
				Involves Mutations	1/18
				Involves changing the organism's traits	1/18

ERQ's Analysis. Through the analysis above, it is evident that some misconceptions are more prevalent than others. The analysis is summarized in Table 4.13.

Table 4.13

Summary of Analysis of ERQ responses

Question	Relevant Study Aspects		Analysis
How does a gene for a particular trait actually make that trait happen? For example, how does a gene for dimples make the individual end up having them.	150.	Relate micro (gene) to macro (trait)	Most students struggled to understand the difference between cell expression and gene transmission and integrated components of inheritance in this section.
	151.	Gene ontology	
Each type of species has their distinct chromosome number. Humans have a chromosome number of 46, while chimpanzees have a number of 48. If I somehow managed to successfully add 2 pairs of chromosomes to a human stem cell so that it will have 48 chromosomes, what do you think will happen? will this cell develop into a chimpanzee cell? why or why not?	152.	Relate micro (chromosome) to macro (organism)	Most students were successfully able to recognize that different species, regardless of whether they share s similar number of chromosomes or not, are different due to the genes carried per chromosome and hence they cannot simply add or remove chromosomes to change species. Students who did so successfully were able to relate micro aspect of chromosomes to the macro organism as a whole whilst being aware of the ontology of chromosomes in their role of carrying genes. Very few students though such was possible.
	153.	Ontology of chromosomes	

What is meant by the genetic code is universal? explain how the genetic code is universal.	154.	Ontology of genes	Only one third of the students successfully explained what is meant by the genetic code being universal in regards to relating codons to the amino acid they code for .A small portion of the students assumed that a universal genetic code meant an identical genetic code sequence which is not the case,
In your own words, explain how Genetically Modified Organisms (GMOs) are produced, such as insulin producing bacteria.	155.	Relate micro (gene and microscopic processes) to macro (product)	Not many students addressed the targeted conceptions in their answer, students seemed to perform most poorly on this ERQ. This may be due to the fact that it was administered online during the quarantine period. Most students' answers lacked depth but also very few actually had misconceptions regarding the concept.

Videotaped Class Lessons, Student Work and Teacher Journal. Data from the class was also used to analyze students' progress throughout the study. In this section, excerpts from the lesson transcriptions and teacher reflection will be discussed along with the student work. The focus on the student work will be mainly through *The Project* discussed in Chapter III as it was a significant assignment that encompassed many conceptions.

Videotaped Class Lessons. The videotaped then transcribed lessons allowed for a recorded encounter between the teacher and students. Even though the transcripts of the videotaped lessons were not analyzed in detail because the scope of the study being a master's degree, two examples are presented to illustrate the type of interactions that took place between the teacher and the students. For example, the encounter below from lesson 8 shows how the teacher guides the student into distinguishing between two similar concepts describing chromosomes.

Student 15: Wait a minute, bivalents are not homologous chromosomes?

Teacher: They are, but it's when they are paired up. Yes Student 23.

Student 23: So, mitosis doesn't have bivalence?

Teacher: No

Student 23: How?

Teacher: I have homologous chromosomes, but they do not pair up together and you do not separate them. Meaning I have chromosome maternal, and chromosome paternal [gestures in air]. Because I am only separating the sister chromatids of each…

Student 22: Ms. Synapses is the process that makes the bivalents?

Teacher: Synapses is when they are bonded, and they start the process of crossing over. Okay so it relates to crossing over

Furthermore, the lesson transcripts also showed student enquiry in the class which could be an indicator of their present misconceptions. Examples of such are shown below in Table 4.14.

Table 4.14

Student input and commentary across sample lessons

Student Input	Commentary
Lesson 5, Student 23: When they are connected by a centromere it counts as one or two? Lesson 5, Student 4: When it's drawn like this is it considered sister chromatids? Lesson 5, Student 16: How can we tell if a gene has a different allele or is a different gene? Lesson 6, Student 20: If the disease starts from one cell, how does it affect the whole organism. I mean the child starts from the egg cell, right?	In this lesson, the teacher was using the same chromosome sketches to represent different "names" that can be used to describe chromosome including while they are replicated such as asked by student 23 and 4. The student actively begins to distinguish between the ontology of the two concepts through the direct instruction. The students also begin to form links between the micro and the macro, in this case the micro is the cell and the student attempts to understand the connection between the cell and the whole organism

Teacher Journal. Throughout the course of the study, the researcher/teacher reflected on the lessons and student performance actively. Those reflections are discussed in this section.

One of the benefits of being both the researcher and the teacher in a study is that one gets immediate feedback regarding what is effective and what is not without having to wait till the end of the study which allows for some "tweaking" to ensure the students benefits. For example, As a teacher who is the researcher, I am able to integrate multiple representation-related terms in my explanation and when I am addressing questions, and I

used it in the lesson for example stating that this is “used as a symbol to denote” or asking, “what do the different colors represent?”. For example, in this lesson five, we discussed different terms to describe genetic material, and how we use each name to describe a particular form of condensed DNA, in a particular stage or situation. We also discussed the image that the students mentally have of DNA which is the replicated chromosome and how it is not an accurate representation of chromosome since it is replicated in that form. Using the same model in particular contexts allowed the students to make links that might have been missing prior to the instruction. Furthermore, hand-in-hand with the visuals, I also used the questioning method to help students come up with conclusions regarding when each DNA-related terminology is used, and how these DNA-elated concepts are linked to different familiar processes. These visuals, which can be labeled as symbols helped make the link between the molecular/micro DNA-related concepts and more observable concepts and/or processes such as Karyogram and cellular division.

Furthermore, the questions asked by the students in the session suggest that the students began understanding the nuances that distinguish one term from the other, and the symbols used to distinguish them. Overall, I was pleased by the quality of questions asked as I felt it reflected the type of thinking I want them to have. I felt the tools- visuals- along with the prompting questions were very effective in making those links.

One of the re-occurring weaknesses addressed in the teacher reflections was the absence of hands-on activities that allowed the students to manipulate the abstract concepts in a manner to make them more “tangible”. Whilst the visual aids played a significant role in bridging those concepts, they were was not sufficient for students to see links among the different representations. To compensate for this, the students were assigned a somewhat substantial assignment that allowed them to manipulate the concepts that they did not have the opportunity to do so in class. This is discussed in this next section.

Towards the end of the study, when the instruction transitioned from class to the online platform due to the COVID-19 pandemic, much of the teacher reflection focused on the challenges of teaching online, the decrease in study engagement, performance and quality of work. Students did not seem to take the online platform seriously which impacted the results of the study. This aspect is discussed in more detail in the upcoming chapter.

Student Work, "The Project". As mentioned before, *The Project* was assigned towards the end of instruction after covering 3.1-3.4 of the chapter and before starting the last section (3.5). In the genetics chapter, chapter 3, the first four sections discuss genes (3.1), chromosomes (3.2), meiosis (3.3) and inheritance (3.4). These sections discuss microscopic concepts (genes and chromosomes) and processes (meiosis), then puts these concepts in context when discussing how they contribute to inheritance (3.4) which leads to macroscopic outcomes (observable physical traits). After thoroughly studying these sections, the teacher assigned a project that aimed to incorporate all the concepts learned into a relevant context. What made *The Project* different than other assignments is that it encompassed a wide spectrum of concepts, both microscopic, macroscopic and symbolic all in one context.

The project gives the students 23 pairs of male and female "chromosomes" (in the form of paper-cutouts) and ask them to use these to represent the different processes/states discussed in the four sections of the chapter. The chromosomes were labeled by number for each of the male and the female, with at least one pair of symbols on each chromosome pair (as shown in Figure 4.1), and each chromosome pair there was a separate key given to students to "decode" those symbols to what trait they represented (as shown in Figure 4.2). The symbols drawn, that encompassed both letters and shapes, were meant to represent alleles.

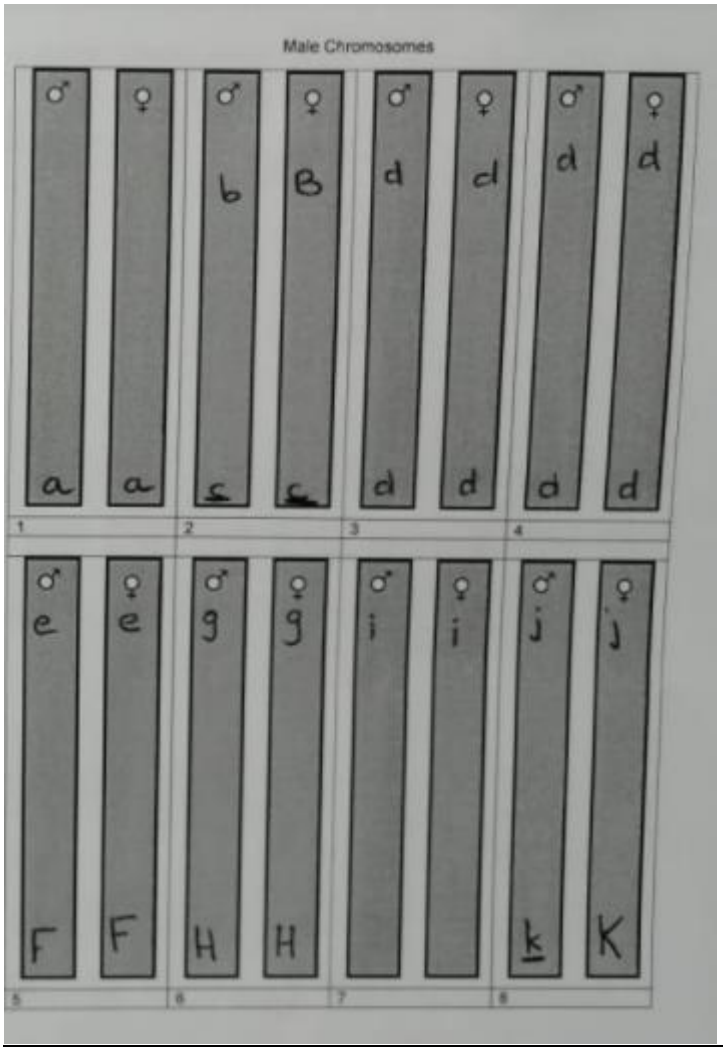


Figure 4.1. Male Chromosomes pair 1-8 with the symbols drawn on them.

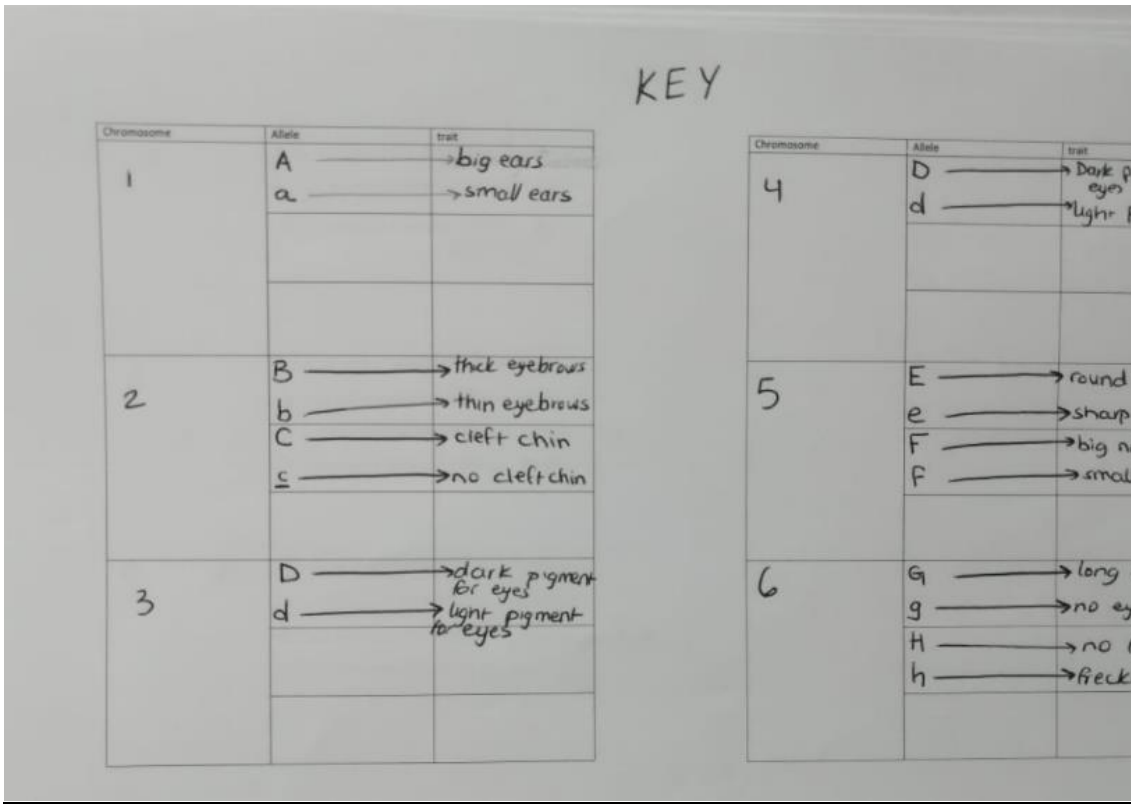


Figure 4.2. Key for Chromosomes pair 1-6 (foor both male and female) ; Capital letters denoted dominant traits whilst lower-case letters denoted recessive traits.

Students were required to first take a picture of the female and male chromosomes before cutting them, so they have a reference picture to avoid confusion later in case the chromosomes are mixed. Then, the students were asked to denote the symbols on the chromosomes for the male and the female chromosomes to infer the physical traits of the male and female individuals. This task required the students to link the genotype (symbols/alleles/ microscopic) to phenotype (macroscopic) by using the chromosome cutouts and the symbols on them (symbolic). Other requirements included asking them to create a karyogram for the male and female (which is an image of the replicated chromosomes taken during mitosis/meiosis), recreate the state of chromosomes during the process of mitosis and meiosis, and then using the gametes produced in this meiosis trial to mimic fertilization and create an "off-spring" with the combination of the female and male

sex cells. Then using these combinations and the zygote created, the students needed to infer the physical traits of the off-spring (using the key from Figure 4.2) and draw the off-spring to represent how it looks like. This project not only encompasses most of the concepts discussed across of the four sections of the chapter, but also relates them all under one context that incorporates. Macro, micro and symbolic (project assignment found on Appendix 13).

This project was assigned during a time where the students were meant to have a week off as holiday, however this deadline was extended as this holiday was pushed due to COVID-19 related events. The students had sufficient time to work on this project, were allowed to work in pairs, and were asked to submit picture evidence of the requirements. Students reached out to the teacher throughout the duration of the project to ask questions and confirm details prior to the deadline. The question-answer process was perceived as educational because it showed the students misunderstandings regarding genetics-related concepts when required to put them all in context. Of the questions asked, some are displayed below in Table 4.15.

Table 4.15

Student Questions on project and Commentary

Question	**Commentary**
1) How do I differentiate between male and female meiosis and mitosis, yes, I do know that females produce eggs and male sperms, but how would you know when I hand in the project?	The main difference between meiosis and mitosis is the behavior of chromosomes and the distinction of homologues chromosomes in meiosis. There is no difference between the male and female mitosis and meiosis except regarding the alleles carried by the chromosomes that divide in both processes, and the 23rd chromosome which is XX for female and XY for male. Because most of the time, students categorize these concepts separately, it could be challenging to see how they overlap in one context.
2) I want to know what happens with the male and female sex chromosome, (as I didn't find anything online or in the book), does a cell carry both XX and XY chromosomes ? the packet only provides one pair of each, so when mitosis process occurs, what happens to them exactly ? Do the chromatids just separate like normal? Shouldn't the two diploid cells at the end only carry XY (if it's male).	Here, the student first fails to recognize that the chromosomes need to replicate before any type of cell division. Furthermore, the student seems to be confused in regards to the twenty third chromosome in particular as it plays a role in determining the gender, failing to realize that the twenty third chromosome pair acts like all the other twenty-two except for the fact that this pair is not identical (in the case of the male)

Books and online diagrams often have a very simplified diagram of the cell division processes, often using four pairs to represent the whole process. By using 23 pairs on a female and male individuals and seeing how those chromosomes act to eventually form sex

cells through meiosis, then showing how fertilization is a combination of any of the formed sex cells and even though the students had the same male and female chromosomes, the resulting off-springs were different due to the randomness of the chromosome behavior in the process. This was discussed in a class online after the project was submitted and was aimed at emphasizing how variation arises through sexual reproduction whilst emphasizing other genetic-related concepts. Hence, even though the project was a very guided assignment, it was still a beneficial learning process on its own.

Other student work. Other student work included Student Supplementary Unit Sheets for every section, and placing concepts within the macro-micro-symbolic triangle, sample of this student work is in Appendix 15B and 15C. Both of these were thoroughly guided assessments where students received feedback and had the chance to fix their work and re-submit, hence student submissions are a not direct indicator of previous misconceptions, however it was the process of asking and giving feedback that was key. The most re-occurring issue for the students was usually separating micro vs symbolic concepts, particularly at the beginning of the instruction as most micro concepts were being represented using symbols and students would often confuse both. Furthermore, another source of confusion was "where to draw the line" between micro and macro entities. This was prevalent when describing cells as students could argue that cells are visible (at least much more than chromosomes and DNA) but only under a microscope. In this case, I was not particular with the categorizing as long as the student justified the choice made.

Summary

Table 4.16 presents a summary of the change in student conceptions throughout the study based on results of analyzing data form all the instruments used in the study. As shown in the table 4.16, with the progress of the study, there is little change in conceptions

shown in the GLAI. As for the two-tier questionnaire, the conceptions also remained relatively the same with the exception of the ontology of the genes as students performed better on the second two-tier questionnaire on the item relating to this concept. The most significant change was shown in the interviews, where with the progress of time, and as shown in the interview analysis table (Table 4.11) the students' understating of the ontological aspect of genes, chromosomes and DNA seemed to improve with a higher frequency of students getting the correct conception towards the end. There is also an improvement in regard to how traits are expressed, understanding how gender is determined and similarities in appearance to parents (when comparing from interview 1 through 4). As for the ERQ's, little to no improvement was demonstrated in student conceptions throughout the study.

Table 4.16

Summary of the Change in Student Conceptions Throughout the Study

	GLAI 1		GLAI2		GLIAI3	
GLAI	1.	Mutations in one cell can influence the whole multicellular organism	1.	Mutations in one cell can influence the whole multicellular organism	1.	Mutations in one cell can influence the whole multicellular organism
	2.	Mutations have no role in Promoting genetic variation	2.	Mutations have no role in Promoting genetic variation	2.	Mutations have no role in Promoting genetic variation
	3.	Presence of a mutation coding for a disease in the genome indicates that this disease will definitely	3.	Presence of a mutation coding for a disease in the genome indicates that this disease will definitely be expressed in the organism	3.	Presence of a mutation coding for a disease in the genome indicates that this disease will definitely
			4.	Mutations produce new genes/ chromosomes /enzymes /cells for the organism		

	be expressed in the organism	5.	the environment plays the largest role in actualizing a trait		be expressed in the organism
4.	Mutations produce new genes/ chromosomes /enzymes /cells for the organism	6.	most traits are determined heavily by genetics with the environment having little effect on complex traits.	4.	Mutations produce new genes/ chromosomes /enzymes /cells for the organism
		7.	The environment plays a major role in determining complex traits.		
5.	the environment plays the largest role in actualizing a trait			5.	the environment plays the largest role in actualizing a trait
6.	most traits are determined heavily by genetics			6.	most traits are determined heavily by genetics

		with the environment having little effect on complex traits.			with the environment having little effect on complex traits.
	7.	The environment plays a major role in determining complex traits.		7.	The environment plays a major role in determining complex traits.
	TWO-TIER1		TWO-TIER2		
TWO-TIER	1.	Different combinations of chromosomes are responsible for the different cells and	9.		Different combinations of chromosomes are responsible for the different cells and function in the body
			10.		Cells divide to form different cells with varying chromosome

function in the body

2. Cells divide to form different cells with varying chromosome number to fulfill different functions

3. Genes are the smallest unit of structure in a chromosome.

4. Genes are a segment in a DNA molecule.

5. If both a female and

number to fulfill different functions

11. If both a female and male are affected by a disease, then it must be autosomal

12. If the parents are normal but one of the offspring is affected, then the disease is definitely autosomal recessive

13. To check whether an organism is heterozygous or homozygous dominant, crossing with another homozygous dominant will yield observable results

14. To check whether an organism is heterozygous or

	male are affected by a disease, then it must be autosomal	homozygous dominant, crossing with another heterozygous will yield observable results
6.	If the parents are normal but one of the offspring is affected, then the disease is definitely autosomal recessive	
7.	To check whether an organism is heterozygous or homozygous dominant, crossing	

		with another homozygous dominant will yield observable results					
	8.	To check whether an organism is heterozygous or homozygous dominant, crossing with another heterozygous will yield observable results					
	Interview 1		Interview 2		Interview 3		Interview 4
Interview	1.	Confusion between the	5.	you cannot have homologous	7.	Defines genotype as	3. struggle with

	concept of the 23rd sex chromosom 6. e which carries the sex-linked genes with the concept of sex cell that carries heritable material that will be used in fertilization	chromosomes and sister chromatids at the same time Student cannot determine how to distinguish DNA from gene	1.	outcome of genes Inheritance plays no role in genetic mutations. It is merely an error in transcriptio n and translation. (source not discussed)	concept s of mutatio ns and genetic diseases
2.	Whether a trait will be expressed in the off-spring or not, it is determinant on whether it is		2.	struggle with concepts of mutations and genetic diseases	

		dominant or recessive when carried by the parents					
	3.	Meiosis does not play a role in the degree of resemblance between parents and offspring					
	4.	Meiosis does not play a role in variation between siblings					
	ERQ 1		ERQ 2		ERQ 3		ERQ 4
ERQ	1.	Confusion between gene expression	1.	Chromosomal abnormalities are equivalent to DNA	1.	Stating the genetic code “is the same” with	Brief/Naïve description of the process of

	and gene transmission 2.	abnormalities/mutations	no further elaboration or	creating a GMO
2.	Whether a trait will be expressed in the offspring or not, it is determinant on whether it is dominant or recessive when carried by the parents	3. Changes of chromosome number introduces new traits/ traits from another species 3. Animal cells are flexible and can change to any type of animal cell by manipulating chromosome number	2. explanation 2. Genetic code is the same meaning they have the same nucleotides 3. Mention codons without mentioning amino acids/proteins	

CHAPTER V

DISCUSSION

The chapter is organized as follows: The first part presents a summary of the research findings described in the previous chapter, and a discussion of these findings. Furthermore, this chapter also discusses implications for instruction, in regard to teacher training and curriculum development. Limitations, in regard to the tools, instruction along with the setting of when and where the study was implemented, are also discussed. The chapter concludes with recommendations for further research in light of these findings.

Summary and Discussion

The purpose of this study is twofold: (1) to identify misconceptions that Year 1 International Baccalaureate students have regarding the topic of genetics (2) to investigate the effect of a macro-micro-symbolic teaching approach that integrates ontological elements on students' conceptual understanding of genetic concepts.

To address the first research question, a Genetics Literacy Assessment Items (GLAI), items from a Two-Tier questionnaire, an extended response question (ERQ) and an interview were administered to detect students' initial genetic conceptions. In alignment with the literature review, the students seemed to struggle to, "alternate between the concept of a gene and its outcome (the trait; the phenotype)" (Bahar *et al*.,1999), have "a low level of progression in the conceptual understanding of major genetics concepts, specifically the microscopic, macroscopic relation between gene and trait…genotype, and phenotype" (Osman, BouJaoude & Hamdan, 2016), struggle with the ontology of a gene (Duncan & Reiser, 2007).

These challenges and misconceptions were meant to be addressed by the instructional materials in the study and it was expected that there would be an improvement in student performance on the consecutive GLAI, two-tier and ERQ tasks. This expectation was based on previous research that integrated multiple-level instruction (similar to the instructional methodology used in this study) that yielded improvement of student understanding and performance (Treagust & Chandrasegaran, 2009; Jaber & BouJaoude, 2012). However, this expectation was not fulfilled as the students showed little to no improvement in the areas they struggled with.

At the beginning of the study, results from analyzing data from the first GLAI test, two-tier questionnaire, first ERQ and interviews show that students struggled with relating micro concepts to macro ones and with the ontology of genes. As mentioned above, these aligned with the results of research in the literature review (Bahar *et al*., 1999; Duncan & Reiser, 2007; Osman, BouJaoude & Hamdan, 2016)

The results from the consecutive GLAI, two-tier, ERQ's and interviews were disappointing in comparison to the expected outcome. It was expected that students' conceptions would improve throughout the duration of the study to parallel results in similar studies that followed a similar instruction (Treagust & Chandrasegaran, 2009; Jaber & BouJaoude, 2012). However, the students in this study did not display similar significant improvement as shown in the aforementioned studies.

As will be discussed in more detail in the limitations section, the COVID-19 situation along with the response of the government in regard to school regulations contributed to the students' decreased performance and quality of work. Towards the end of the study, many of the students stopped contributing whatsoever, and the quality of work of those that were still engaged was significantly lower.

Results from the consecutive tests did not show significant improvement in the existing challenges faced by the students. The aforementioned struggle seemed to remain consistent throughout the study, particularly the struggles relating to linking micro to macro. Students seemed to group micro concepts separately from the macro ones, that are an outcome of these micro processes. For example, when discussing the inheritance of a particular trait, the students found difficulty in tracing how this trait can be passed form parent to offspring through the processes of meiosis (in each parent) and then fertilization which leads to the inheritance of a particular allele combination, even though, the same students could solve complex pedigree charts and predict inheritance patterns. This aligned with research on student challenges in genetics conducted by Knipples, Waarlo and Boersma (2005). This was particularly evident in *The Project* (Appendix 13), which was an assessment that required the students to put different microscopic concepts and processes in one context to produce a macroscopic result (the phenotype of the offspring). Even though the assessment was broken down into multiple small steps that students were familiar with, the overall task was still overwhelming to many.

Implications for Teaching and Learning

As both the researcher who conducted this study, and the teacher applying the instruction, the opinion described under this section might be somewhat biased, however efforts were made to remain objective. As a teacher, writing daily reflections on the lessons given served as a useful tool to reflect on instruction and methodology. In light of this, one can recommend that educators incorporate reflections in their daily practice as a guide and tool of improvement in the classroom.

Secondly, incorporating larger assessments that include several concepts could be a powerful learning and assessing tool as it challenges the students who might have previously "categorized concepts separately" to "unbox" those concepts and rearrange them to a more comprehensive context (the assessment objective). This was demonstrated in the assignment of *The Project*, that incorporated information and concepts from the first four sections out of the total five of the chapter.

Thirdly, the importance of using particular models/symbols when describing a microscopic concept or process. The symbol used influences, to a large extent, the students' understanding. It is important to discuss the limitation of using this symbolic representation in representing the actual microscopic concept/process. In other words, when using a symbol to represent a microscopic concept or process it is important to be explicit on the degree of accuracy this symbol represents the actual microscopic process/concept, and what limitations it has when representing it. For example, when using simple diagrams to describe meiosis, and using 4 chromosome pairs instead of the 23, it is important to emphasize the difference between using this simplified model, and the actual human cell with 23 pairs. This is significant when discussing variation that arises from the crossing over that happens between chromosomes, the shuffling of the chromosomes throughout meiosis, and different gametes resulting from that.

Furthermore, it is not enough to be reflective on the symbols used and their limitations, it is also important to be consistent when using particular symbols. The importance of being consistent with using the representations is necessary so that the students can keep actively making connections between the given symbol and the concept it represents. This can be explained using an example on chromosomes. As can be gleamed form the IB genetics curriculum, the genetic material can have different

names depending on the state in which it exists (condensed, not condensed, replicated, paired etc.). Hence, when using particular symbols to represent this genetic material, it is useful to be consistent with the type of symbol used when describing the different states of the genetic material. This was evident in the instruction when a certain sketch of chromosomes was used consistently (same color, size) but in different states to show the different "states of DNA". This emphasized the notion that "it is all DNA", and the difference was in the terminologies used in the curriculum and the lesson plans (homologues chromosomes, sister chromatids, chromosomes, chromatin, etc.). These symbols were made in this study by using a very simple Paint software and did not require much preparation but seemed to have a positive influence on the students' understanding. This was also utilized when assigning *The Project*, where students were given "chromosome cut-outs" and were asked to use those cut-outs in different contexts to fulfill different tasks that addressed different concepts. This included a multitude of microscopic processes and concepts such as meiosis and fertilization. The chromosomes were also used as carriers of particular alleles that indicated the physical features of the "mom", "dad", and "off-spring" which allowed the incorporation and linking of the symbolic and macroscopic aspects as well.

Lastly, and what was brought to the researcher's attention due to the circumstances, is the importance of training teachers to incorporate technology in their teaching and using online platforms for asynchronous teaching and learning. Present technologies available for schools and educators should be taken advantage of and teachers should be trained to make use of these platforms. Many of these technologies can enhance the learning and teaching experience even with the absence of negative situations. Training teachers on incorporating these software packages in their daily

instruction can aid in the teacher-student feedback loop where the teacher can get more feedback on student performance through these technologies than through more traditional methods. More importantly, the teachers should practice using these tools and teach online under normal circumstances so that students start accepting online teaching as a legitimate teaching approach and take it seriously. One of the possible reasons for the disappointing results of the second part of the study during which multiple representations were being used was apparently the fact that students did not take online learning seriously; this was added to the Ministry of Education's decisions which provided the students the opportunity not to take online teaching seriously because of the freedom give to students not to attend classes and the fact that the grades could not be lower than those achieved prior to disruption caused by COVID 19.

Limitations and Suggested Improvements

In general, given the relative novelty of this study, there were several limitations that influenced the results. That, along with the setting in which the study was done, which was during the COVID-19 Pandemic, had a major influence on the results produced, particularly towards the end of the study. These variables are discussed in this section.

Context and Circumstances

As mentioned in the first section of Chapter IV, the study was implemented in alignment with the time where the COVID-19 struck. Around a quarter of the remaining lessons, the last GLAI test, the second two-tier questionnaire and the interview sets were done online/digitally. Not only that, but there was also a "break in instruction" during that time. This was due to following, after three-quarters of the chapter where sections 3.1 to 3.4 of the chapter were covered, the students had a week off because of a

national holiday. During this week they were supposed to work on *The Project*, which was planned to recap all the studied material, before coming back to school and starting section 3.5, the last section of the chapter. However, due to the outbreak of COVID-19, which coincided with the time of the break, last minute decisions were made by the Ministry and the school regarding when school was supposed to restart. Hence, in addition to the holiday (the week off) the students had another week off as decide by the Ministry for students, teachers, and schools in general to cope with the COVID-19 situation assuming the situation would improve. However, with the rising number of COVID-19 cases, the Ministry decided that schools should be closed a second week. During those two weeks teachers were forbidden from resuming teaching as it was expected that after this time, there will be a return to school and everything will go back to normal. When there was no perceived improvement of the situation, the government then decided to resume school online under strict regulations.

This almost two-week break influenced the students' retention of information and returning to teaching through an online platform did not aid in pulling the students back to the learning environment. To add to that, even after returning to teaching (online), there were many strict regulations regarding how the students were assessed, how their grades were to be handled, and how to deal with disengaged students. These regulations allowed many students to slack off their work or produce work with minimal quality with little to no consequences, and this influenced the students' responses to the study tools (the latter GLAI, Two tier, and ERQs). Furthermore, not only did the quality of effort and work decrease, the decreasing engagement also affected the results of the study and made it more challenging to compare student performance throughout the duration of the study as the number of participants

decreased. For example, during the first GLAI all participants (twenty three out of twenty-three) completed the test, during the second GLAI Test, twenty out of the twenty-three participants completed the test, and on the third GLAI, only fifteen of the twenty-three participants took the test. As a result, the performance of the twenty-three students could not be compared throughout the study. As a result, during the analysis, only the results of the fifteen participants who participated in all three tests were used.

Instruction

Given the relative novelty of this study in regard to applying micro/macro and symbolic representations with reference to concept ontology, there were very few resources to guide the creation of appropriate lesson plans and instruction to support the objective of the study. There were resources on applying micro/macro/symbolic instruction in the field in chemistry, and there were plenty of useful resources on teaching genetics, but very scarce, if any on micro/macro/symbolic instruction with ontological aspects in context of genetics. This forced the researcher to create the instructional materials using those limited guidelines to fit the context of the study. This was done with the aid and insight of a peer teacher. While these materials addressed the objective of the study, there is still room for improvement with increased research on the particular topic of the study. These instructional materials can now be improved based on student feedback to address the study's context more specifically,

Instruments

The tools utilized in the study could be considered essential in determining whether or not the study would succeed in change students misconceptions about genetics concepts. Having "inaccurate" tools that do not measure the result accurately can cause a "faulty reading" of the results. This means that even though the tools did not

provided evidence of significant improvement in student understanding, the class interaction and student discussions did show some potential in regard to the instruction's potency. Hence, the validity of the tools in measuring the potency of the study might have played a role in displaying negative results.

As mentioned in the previous section, the novelty of the study resulted in several limitations, including a limitation regarding the instruments used to measure the potency of the instruction. Given the relative novelty of this study, there were very few resources to use as tools. As a result, existing diagnostic genetics-related tools were used and modified to fit the scope of the study which might have caused the results to be less refined than they should. For example, the GLAI, even though it is a well cited genetics diagnostic tool, had many concepts that the students did not directly deal with throughout the IB genetics unit. As a result, several items out of the thirty-item test were not useful in the context of the study. Similarly, the two-tier questionnaire, of which only seven items were used, addressed a very small portion of the covered concepts, and hence gave limited insight on student conceptions.

As for the interview questions and the ERQ's, even though the questions featured on them aligned better with the International Baccalaureate (IB) genetics curriculum, and related better to the study's objective in regards to relating to multiple representation and integrating the ontological aspect, the questions were still relatively new and needed some modification. This was because they were created and analyzed by the researcher with the aid of a colleague teacher. However, with the feedback and responses of the students, and further research within this context, these instruments can be "tuned" and improved to address the study objective more precisely.

Recommendations for Research

Given the circumstances during which the study was conducted, and the aforementioned limitations, one can argue that the results were not as accurate as they could be in regard to testing the potency of a multiple representation instruction. This was due to two main reasons, the COVID-19 situation and the relative novelty of the study. With the presence of these obstacles there were still positive results shown in the understanding of the students, particularly shown during the interview where students were asked to share their understanding in a more direct manner with the researcher. These results along with the strong theoretical foundations of the objectives of the instructional approach support the notion that the study should be repeated under more convenient circumstances, and that with increasing research in this topic specifically and the enrichment of resources to support the investigation, more positive results will be yielded.

Furthermore, it should also be considered that the study be redone in a context where there is an experimental group and a control group. This would allow for a direct comparison in regard to the influence of applying such instruction versus the lack of such instruction and the influence of that on student understanding.

In addition to that, the study should also be implemented in a more diverse context. Even though the International Baccalaureate, as the name suggests, is an international program that is taught globally, the school in which the study was applied had very little diversity and hence limited representation of global students. The school in which this study was conducted had 98% local students of similar backgrounds and socio-economic levels. This means that the results of this study, even if more positive, could not be applied internationally as it involved the local students only. It is also important to note that it was a segregated school with only boys, hence the female factor

was absent. Having the study in a non-segregated, more international environment can produce results that are more applicable to students world-wide.

Lastly, the research should also be considered in a context where the teacher is not the researcher. This will ensure that the instruction can be communicated and applied by teachers who are not directly involved in the research. This would ensure that the instruction and methodology can be applied by teachers even if they lack the theoretical knowledge of the background of the study.

APPENDICES

Appendix 1-
IB Genetics Syllabus

3.1 Genes	
Nature of science: Developments in scientific research follow improvements in technology—gene sequencers are used for the sequencing of genes. (1.8)	
Understandings: 1. A gene is a heritable factor that consists of a length of DNA and influences a specific characteristic. 2. A gene occupies a specific position on a chromosome. 3. The various specific forms of a gene are alleles. 4. Alleles differ from each other by one or only a few bases. 5. New alleles are formed by mutation. 6. The genome is the whole of the genetic information of an organism. 7. The entire base sequence of human genes was sequenced in the Human Genome Project. **Applications and skills:** 1. Application: The causes of sickle cell anemia, including a base substitution mutation, a change to the base sequence of mRNA transcribed from it and a change to the sequence of a polypeptide in hemoglobin. 2. 3. Application: Comparison of the number of genes in humans with other	**International-mindedness:** 1. Sequencing of the human genome shows that all humans share the vast majority of their base sequences but also that there are many single nucleotide polymorphisms that contribute to human diversity. **Theory of knowledge:** 2. There is a link between sickle cell anemia and prevalence of malaria. How can we know whether there is a causal link in such cases or simply a correlation? **Aims:** 3. **Aim 7:** The use of a database to compare DNA base sequences. 4. **Aim 8:** Ethics of patenting human genes.

Topic 3: Genetics

Essential idea: Every living organism inherits a blueprint for life from its parents.

3.1 Genes	
Guidance: 1. Students should be able to recall one specific base substitution that causes glutamic acid to be substituted by valine as the sixth amino acid in the hemoglobin polypeptide. 2. The number of genes in a species should not be referred to as genome size as this term is used for the total amount of DNA. At least one plant and one bacterium should be included in the comparison and at least one species with more genes and one with fewer genes than a human. 3. The Genbank® database can be used to search for DNA base sequences. The cytochrome C gene sequence is available for many different organisms and is of particular interest because of its use in reclassifying organisms into three domains. 4. Deletions, insertions and frame shift mutations do not need to be included.	

3.2 Chromosomes	
Nature of science: Developments in research follow improvements in techniques—autoradiography was used to establish the length of DNA molecules in chromosomes. (1.8)	
Understandings: 1. Prokaryotes have one chromosome consisting of a circular DNA molecule. 2. Some prokaryotes also have plasmids but eukaryotes do not. 3. Eukaryote chromosomes are linear DNA molecules associated with histone proteins. 4. In a eukaryote species there are different chromosomes that carry different genes. 5. Homologous chromosomes carry the same sequence of genes but not necessarily the same alleles of those genes. 6. Diploid nuclei have pairs of homologous chromosomes. 7. Haploid nuclei have one chromosome of each pair. 8. The number of chromosomes is a characteristic feature of members of a species. 9. A karyogram shows the chromosomes of an organism in homologous pairs of decreasing length. 10. Sex is determined by sex chromosomes and autosomes are chromosomes that do not determine sex. **Applications and skills:** 1. Application: Cairns' technique for measuring the length of DNA molecules by autoradiography. 2. Application: Comparison of genome size in T2 phage,	**International-mindedness:** 1. Sequencing of the rice genome involved cooperation between biologists in 10 countries. **Utilization:** 1. Syllabus and cross-curricular links: Biology 2. Topic 1.6 Cell division **Aims:** 1. **Aim 6:** Staining root tip squashes and microscope examination of chromosomes is recommended but not obligatory. 2. **Aim 7:** Use of databases to identify gene loci and protein products of genes.

Essential idea: Chromosomes carry genes in a linear sequence that is shared by members of a species.

3.2 Chromosomes	
1. Application: Comparison of diploid chromosome numbers of *Homo sapiens, Pan troglodytes, Canis familiaris, Oryza sativa, Parascaris equorum.* 2. Application: Use of karyograms to deduce sex and diagnose Down syndrome in humans. 3. Skill: Use of databases to identify the locus of a human gene and its polypeptide product. **Guidance:** 1. The terms karyotype and karyogram have different meanings. Karyotype is a property of a cell—the number and type of chromosomes present in the nucleus, not a photograph or diagram of them. 2. Genome size is the total length of DNA in an organism. The examples of genome and chromosome number have been selected to allow points of interest to be raised. 3. The two DNA molecules formed by DNA replication prior to cell division are considered to be sister chromatids until the splitting of the centromere at the start of anaphase. After this, they are individual chromosomes.	

3.3 Meiosis

Nature of science:

Making careful observations—meiosis was discovered by microscope examination of dividing germ-line cells. (1.8)

Understandings:

One diploid nucleus divides by meiosis to produce four haploid nuclei.

The halving of the chromosome number allows a sexual life cycle with fusion of gametes.

DNA is replicated before meiosis so that all chromosomes consist of two sister chromatids.

The early stages of meiosis involve pairing of homologous chromosomes and crossing over followed by condensation.

Orientation of pairs of homologous chromosomes prior to separation is random.

Separation of pairs of homologous chromosomes in the first division of meiosis halves the chromosome number.

Crossing over and random orientation promotes genetic variation.

Fusion of gametes from different parents promotes genetic variation.

Applications and skills:

Application: Non-disjunction can cause Down syndrome and other chromosome abnormalities.

Application: Studies showing age of parents influences chances of non-disjunction.

Theory of knowledge:

1. In 1922 the number of chromosomes counted in a human cell was 48. This remained the established number for 30 years, even though a review of photographic evidence from the time clearly showed that there were 46. For what reasons do existing beliefs carry a certain inertia?

Utilization:

2. An understanding of karyotypes has allowed diagnoses to be made for the purposes of genetic counselling.

Syllabus and cross-curricular links: Biology
Topic 1.6 Cell division
Topic 10.1 Meiosis
Topic 11.4 Sexual reproduction

Aims:

3. **Aim 8:** Pre-natal screening for chromosome abnormalities gives an indication of the sex of the fetus and raises ethical issues over selective abortion of female fetuses in some countries.

3.3 Meiosis	
1. Application: Description of methods used to obtain cells for karyotype analysis e.g. chorionic villus sampling and amniocentesis and the associated risks. 2. Skill: Drawing diagrams to show the stages of meiosis resulting in the formation of four haploid cells. **Guidance:** 3. Preparation of microscope slides showing meiosis is challenging and permanent slides should be available in case no cells in meiosis are visible in temporary mounts. 4. Drawings of the stages of meiosis do not need to include chiasmata. 5. The process of chiasmata formation need not be explained.	

3.4 Inheritance	
Nature of science: Making quantitative measurements with replicates to ensure reliability. Mendel's genetic crosses with pea plants generated numerical data. (3.2)	
Understandings: 1. Mendel discovered the principles of inheritance with experiments in which large numbers of pea plants were crossed. 2. Gametes are haploid so contain only one allele of each gene. 3. The two alleles of each gene separate into different haploid daughter nuclei during meiosis. 4. Fusion of gametes results in diploid zygotes with two alleles of each gene that may be the same allele or different alleles. 5. Dominant alleles mask the effects of recessive alleles but co-dominant alleles have joint effects. 6. Many genetic diseases in humans are due to recessive alleles of autosomal genes, although some genetic diseases are due to dominant or co-dominant alleles. 7. Some genetic diseases are sex-linked. The pattern of inheritance is different with sex-linked genes due to their location on sex chromosomes. 8. Many genetic diseases have been identified in humans but most are very rare. 9. Radiation and mutagenic chemicals increase the mutation rate and can cause genetic diseases and cancer.	**Theory of knowledge:** 1. Mendel's theories were not accepted by the scientific community for a long time. What factors would encourage the acceptance of new ideas by the scientific community? **Utilization:** Syllabus and cross-curricular links: Biology Topic 1.6 Cell division **Aims:** 2. **Aim 8:** Social implications of diagnosis of mutations, including the effects on the family and stigmatization.

Essential idea: The inheritance of genes follows patterns.

3.4 Inheritance	
Applications and skills: 1. Application: Inheritance of ABO blood groups. 2. Application: Red-green colour blindness and hemophilia as examples of sex-linked inheritance. 3. Application: Inheritance of cystic fibrosis and Huntington's disease. 4. Application: Consequences of radiation after nuclear bombing of Hiroshima and accident at Chernobyl. 5. Skill: Construction of Punnett grids for predicting the outcomes of monohybrid genetic crosses. 6. Skill: Comparison of predicted and actual outcomes of genetic crosses using real data. 7. Skill: Analysis of pedigree charts to deduce the pattern of inheritance of genetic diseases. **Guidance:** 8. Alleles carried on X chromosomes should be shown as superscript letters on an upper case X, such as X^h. 9. The expected notation for ABO blood group alleles is: *Phenotype* O *Genotype* ii a. I^{AA} or I^A b. I^{BB} or $I^B i$ AB $I^A I^B$	

3.5 Genetic modification and biotechnology

Nature of science:

Assessing risks associated with scientific research—scientists attempt to assess the risks associated with genetically modified crops or livestock. (4.8)

Understandings:

1. Gel electrophoresis is used to separate proteins or fragments of DNA according to size.
2. PCR can be used to amplify small amounts of DNA.
3. DNA profiling involves comparison of DNA.
4. Genetic modification is carried out by gene transfer between species.
5. Clones are groups of genetically identical organisms, derived from a single original parent cell.
6. Many plant species and some animal species have natural methods of cloning.
7. Animals can be cloned at the embryo stage by breaking up the embryo into more than one group of cells.
8. Methods have been developed for cloning adult animals using differentiated cells.

Applications and skills:

9. Application: Use of DNA profiling in paternity and forensic investigations.
10. Application: Gene transfer to bacteria using plasmids makes use of restriction endonucleases and DNA ligase.
11. Application: Assessment of the potential risks and benefits associated with genetic modification of crops.
12. Application: Production of cloned embryos produced by somatic-cell nuclear

Theory of knowledge:

1. The use of DNA for securing convictions in legal cases is well established, yet even universally accepted theories are overturned in the light of new evidence in science. What criteria are necessary for assessing the reliability of evidence?

Utilization:

Syllabus and cross-curricular links: Biology
Topic 2.7 DNA replication, transcription and translation

Aims:

2. **Aim 6:** The design of a rooting experiment should ideally lead to the experiment actually being carried out by students.
3. **Aim 8:** The ethics of genetic modification could be discussed.

Essential idea: Biologists have developed techniques for artificial manipulation of DNA, cells and organisms.

3.5 Genetic modification and biotechnology	
1. Skill: Design of an experiment to assess one factor affecting the rooting of stem-cuttings. 2. Skill: Analysis of examples of DNA profiles. 3. Skill: Analysis of data on risks to monarch butterflies of Bt crops. **Guidance:** 4. Students should be able to deduce whether or not a man could be the father of a child from the pattern of bands on a DNA profile. 5. Dolly can be used as an example of somatic-cell transfer. 6. A plant species should be chosen for rooting experiments that forms roots readily in water or a solid medium.	

Appendix 2

Sample Lesson Plan 1

TOPIC:Genetics TIME: 45 MINUTES GRADE LEVEL: 11/ IB DP1

LESSON TITLE: Sickle Cell Anemia (Chapter 3; section 1) SEQUENCE: Lesson 2

PURPOSE

1. Students will learn about the potential effects of mutations in the DNA using sickle cell anemia as an example.
2. Students will link the microscopic/subcellular phenomena which is the DNA mutation to the macroscopic effects of sickl cell anemia.

SCIENCE CONTENT & MAJOR CONCEPTS

3. Sickle cell disease is a group of disorders characterized by misshaped red blood cells. This is due to a mutation affecting Haemoglobin which is the component of red blood cells responsible for carrying oxygen. The mutation that causes this condition is a single base substition in the gene coding for the Haemoglobin. This causes the translation of the amino acid valine instead of glutamic acid. This change from one amino acid to another leads to the change of the structure of the haemoglobin making it less effective.
4. Disease is hereditary and autosomal recessive

LEARNING OUTCOMES /OBJECTIVES

5. Recall that sickle cell anemia is caused by a single base mutation in the DNA
6. Explain the effect of mutation on transciption
7. Explain the effect of mutation on translation
8. Compare the amino acids of typical and atypical hemoglobin in terms of protein structure
9. Predict the effect of changed structure on function of haemoglobin
10. Identify different levels of reresentations for the disorder: the subcellular, cellular and organismal
11. Identify symbols to mediate between the sub-cellular and organismal levels
12. **IB OBJECTIVE:** *Application: The causes of sickle cell anemia, including a base substitution mutation, a change to the base sequence of mRNA transcribed from it and a change to the sequence of a polypeptide in hemoglobin.*

ENTRANCE ABILITIES

13. Students must have background on how proteins are made in the cell through the processes of transciprion and translation
14. Know that codons are made up of three DNA nucleotides and each codon codes for a particular amino acid
15. Amino acids are building blocks of proteins

MATERIALS & EQUIPMENT

16. Handout
17. Video

INSTRUCTIONAL ACTIVITIES

1. Students are given a profile of an individual with an unknown genetic disorder and are given 5 minutes to come up with a list of questions and potential checkups to investigate this patient's case

    a. The patient's profile would describe physical symptoms of: frequent troubled breathing, often felt extremely weak and had to stay at home, pale color.

    b. His profile would also include information on relatives showing similar symptoms indicating the possibility of those symtoms benig linked to a genetic disease.

    c. The answers are then discussed in class and a list is compiled on the board regarding questions and possible check-ups. Ideally students would mention blood testing as a checkup procedure.

2. Students are shown a microscopic picture of the patient's red blood cells then another image of healthy red blood cells to compare. The patient's cells should have an odd shape. Students are asked to compare and conrast the two images and come up with predictions regarding the effect of the misshaped red blood cells on the patient and possible links to the stated symptoms.

3. Students are encouraged to make draw macro/micro/ and symbolic traingle on their notebooks and annotate the diagram starting with the macro corener in what they understand is happening at the organismal/macro scale of the disease.

4. A discussion is propmted on nature of genetic diseases, and what it means for a diseases to be heriditary as a revision of previous content. Students are reminded that genetic diseases are diseases caused by errors in the genetic code and that such diseases, because they are in the DNA, they could be passed down to the offspring.

5. The students are shown a video of a single base substitution mutation in the DNA and a comment is made on how a similar process occuring in a particular gene in the DNA that codes for Haemoglobin that causes the patient's symptoms. Teacher explictly charecterizes the video as a symbolic representation of th mutation process that eventually leads to the sickle cell, and asks the students to update the triangle structure accordingly.

6. A discussion is then prompted on different processes that involve DNA, such processes must include: DNA replication where the DNA is copied prior to cellular

division, transciption an translation where the DNA code is transcribed to RNA and this RNA is translated into amino acid chain forming a protein.

7. The teacher then asks the students on the effect of a nucelotide substitution on those three processes, particularly how changes in DNA can be inherited and how changes in the DNA in particular areas that code for proteins can lead to the formation of a “faulty protein”. The teacher compares the the properties of the amino acid coded by the non-mutant base sequence to the amino acid coded by the mutant one and then shows a 3-D animated model of the protein translated from the non-mutated sequence and the mutated sequence

8. Students are urged to annotate the diagram with what thay understand is hapenning at the cellular and sub-cellular level and what symbols were used to explain these processes.

9. Students are then asked to annotate the diagram with what they percived “symbolic” column with tools/representations used to represent the cellular and sub-cellular process.

10. The teacher prompts a class discussion to explain how the cellular processes involved in muutation eventually lead to the physical symptoms of the patients using what the students know about how the red blood cell looks like, the role of the red blood cell in trasporting oxygen, and the role of oxygen in the body.

Closure And Review

1. At the end of class teacher sums up the lesson by reviewing how a muation in the gene leads up to a defomred protein which causes the symptoms introduced at the beginning of the class.

2. Teacher then asks students to go over the maro/micro/symbolic aspects of the disease as discussed in class earlier and as they’ve written in their notes.

At the end of each lesson, the required content must be explicitly defined to the students within these vertices and sides so that they are aware of where each concept fits within this scheme. Furthermore the students will be asked to fill in the supplementary sheet for the content covered in class as either classwork or homework depending on time constraints.

Appendix 3

Sample Lesson Plan 2

TOPIC:Genetics TIME: 45 MINUTES GRADE LEVEL: 11/ IB DP1

LESSON TITLE: Non-disjunction in Meoisis (Chapter 3; section 3) SEQUENCE: Lesson 6

PURPOSE

3. Students will learn about the effects of the DNA not separating properly during the stages of meiosis (Non-disjunction).
4. Students will link the events in microscopic/subcellular process of meoisis, particularly failure of the DNA molcules to separate during anaphase (Non-disjunction), to the macroscopic effects which is Down Syndrome.

SCIENCE CONTENT & MAJOR CONCEPTS

5. The failure of chromosomes to separate is refered to as Non-disjunction. Non-disjunction refers to the chromosomes failing to separate correctly, resulting in gametes with one extra, or one missing, chromosome

6. It may occur via:
    a. Failure of homologues to separate in Anaphase I (resulting in four affected daughter cells)
    b. Failure of sister chromatids to separate in Anaphase II (resulting in only two daughter cells being affected)
7. Down Syndrome is caused by Non-disjunction
8. Individuals with Down syndrome have three copies of chromosome 21 (trisomy 21)
    a. One of the parental gametes had two copies of chromosome 21 as a result of non-disjunction
    b. The other parental gamete was normal and had a single copy of chromosome 21
    c. When the two gametes fused during fertilisation, the resulting zygote had three copies of chromosome 21
9. Down syndrome is associated with several physical features including:
    a. Flattened facial features; Smaller than average head and ears; Protruding tongue; Short and broad neck, hands, and feet; Poor muscle tone
10. All of the symptoms of Down syndrome exist on a continuum, meaning that they can range from minor to severe

LEARNING OUTCOMES /OBJECTIVES

11. Students understand the different representations of Down Sydnrome
    a. The outcom at the macroscopic level: the physical symptoms and heaalth conditions
    b. The cause at microscopic level: the process of Non-disjuction during anaphase 1 or 2 or meoisis
    c. The value of the symbolic level:
        i. Drawing the process of meisosis using simplified illustrations and how the gamete resulting from this meoitic division will later fuse

with another gamete to produce a zygote with 1 extra copy of a chrosome – in the case of down syndrme this chromosome would be chromsome number 21.

12. **IB OBJECTIVES:**
    a. Skill: Drawing diagrams to show the stages of meiosis resulting in the formation of four haploid cells
    b. Application: Non-disjunction can cause Down syndrome and other chromosome abnormalities.

ENTRANCE ABILITIES

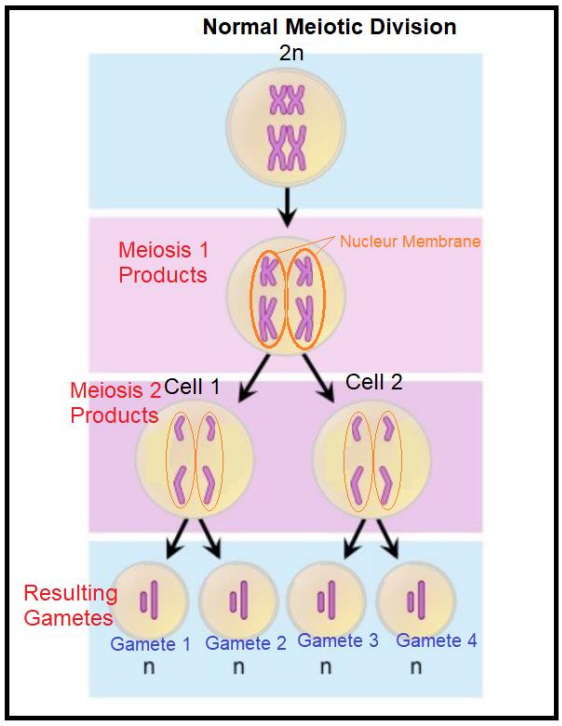
13. Students must have knowledge on the process of meoisis in detail
14. Students must be able to draw a simplified represntations of meoisis showing the behaviour of chromosomes during the different phase
15. Students must know the purpose behind meoisis (the synthesis of gametes that will later fuse)
16. The products of meoisis (gametes with half the number of chromosomes)
17. Students must be familiar with the fertilzation prcooses that joins to gametes and joins their genetic material to form a zygote that will later develop into the offspring.
18. Differentiate between haploid and diploid

MATERIALS & EQUIPMENT

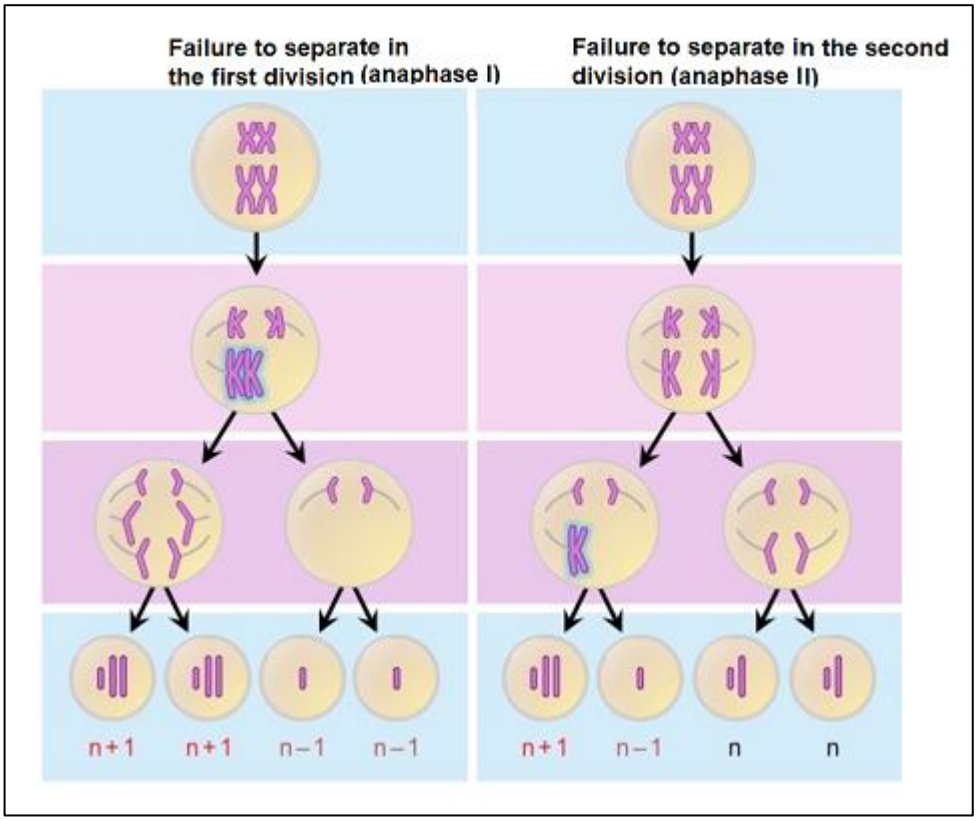
19. Pictures of Individuals with Down Syndrome
20. Video

INSTRUCTIONAL ACTIVITIES

1. Students are asked to draw a **symbolic** representation of a cell with a diplod number of 2 chromosomes going through process of meosis. The digram should denote the condition of the chromomes after each meoitic division. This activity erves as a revision to last lesson's content, and preps for the upcoming material. Product should look like the figure below.



2. The students are then asked to do the same sketch, but this time, they should denote the condition of the chromomes after each meoitic division when there has been a failure of DNA to separate properly in the first meoitic division and in the second. Results should look like the figure below.



3. Teacher then introduces the term "Non-disjunction" and restates the role of their illustrations as **symbolic representations** of the sub-cellular process, and the symbols (2n/n/n-1/n+1) denoting ploidy of the cell.

4. Teaher then raises the question as to what will happen to gametes with irregular number of chromosomes (other n) and the influence of that on the process of fertilaztion/ when the gamete fuses with another gamete. The teacher then asks the students to draw the result of the fusion of regular gamete (with n chromosomes) with different gametes and what different outcomes arise:

   a. n + n = 2n (regular zygote with regular chromosomes number)

   b. n + (n+1) = 2n +1 (zygote with an extra chromosome)

   c. n + (n-1) = 2n -1 (zygote with one less chromosome; less likely to survive)

   the **symbolic** nature of this representation is restated.

5. Teacher introduces Down Syndrome as a result of a non-disjunction that results in on of the gametes having one extra chromosome for chromosome number 21 (in humans), and shows pictures of individuals with varying degrees of Down Syndrome. Indicates that the physical features shown are a **macrorepresenation** of the outcome of the **microscopic process** of Non-disjunction.

6. The physical features and symptoms/effects of down syndrome are then discussed with the class.

7. Students are then asked to make predictions as to how an extra chromosome can bring such an effect (physical features and health issues)

    i. Intermediate processes that mediate between genetic code and protein synthesis

    ii. What kind of information does a human chromosome hold

    iii. The effect of having an extra copy of a chromomes

8. Students areasked to sketch the triangle and fill it in with what was discussed today in class (vertices and sides)

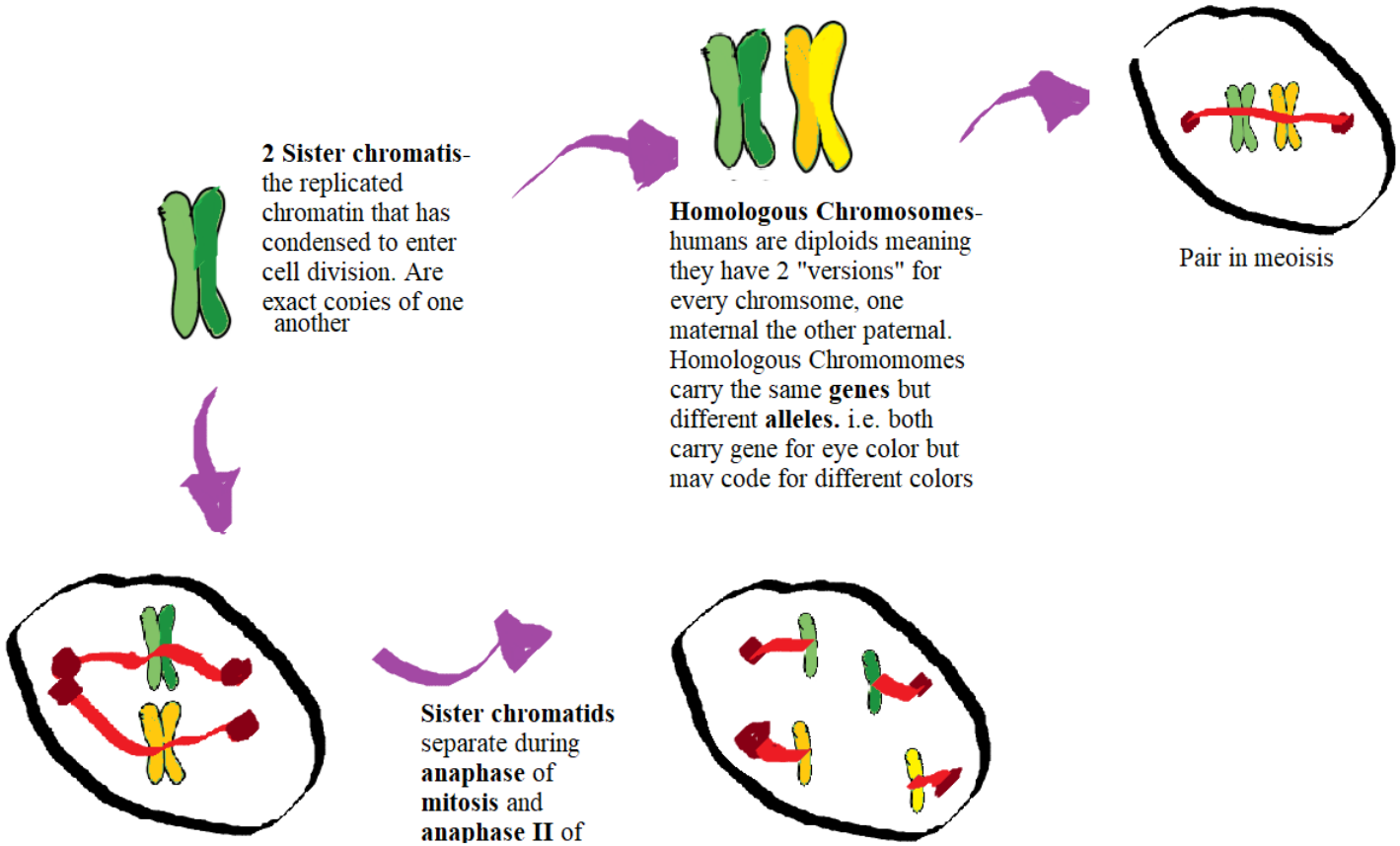
9. The teacher then asks the students to research the genes present on the human 21st chromosome as homework so the discussion on how this extra chromsome could have lead to the physical aspects of Down Syndrome.

    a. The homework results will be discussed at the beginning of the next lesson and conclusions will be drawn from the stuents' search results regarding the link between genes on chromosome 21 and the physical aspects of down symdrome.

At the end of each lesson, the required content must be explicitly defined to the students within these vertices and sides so that they are aware of where each concept fits within this scheme. Furthermore the students will be asked to fill in the supplementary sheet for the content covered in class as either classwork or homework depending on time constraints.

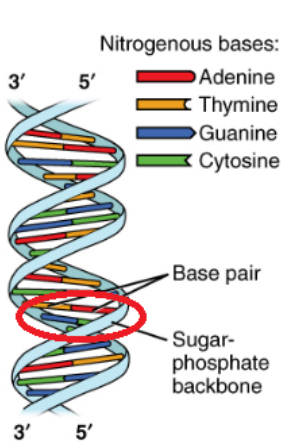
Appendix 4: Student Resources: Note Summaries

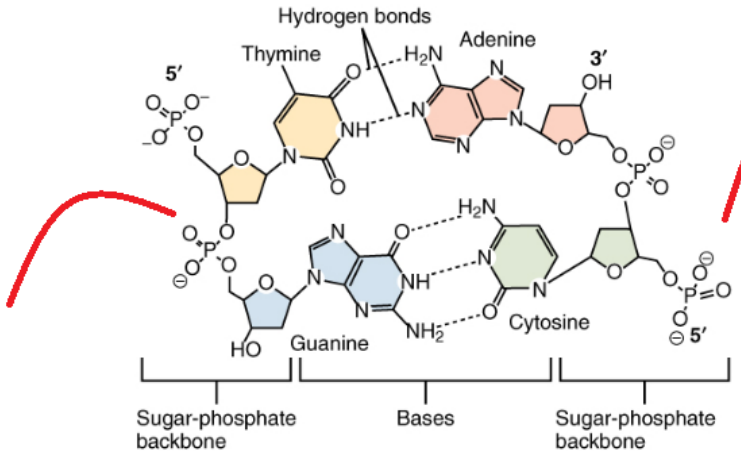
Re-cap of genetics terms in context:



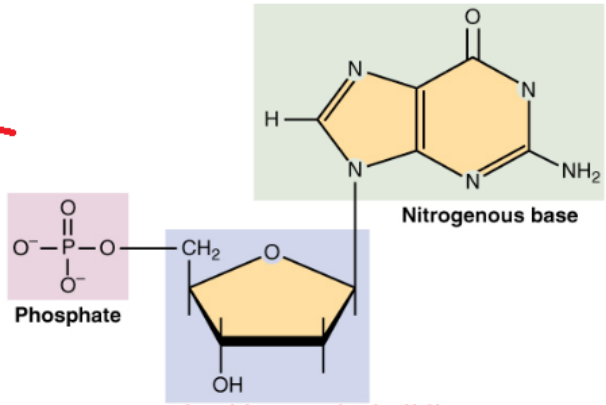
Appendix 4: Student Resources: Note Summaries

Structure of DNA:



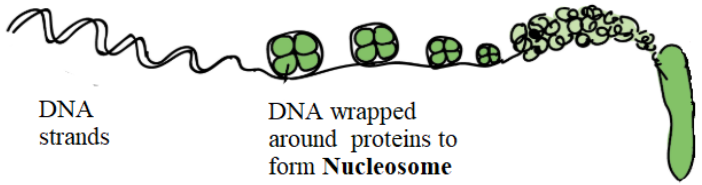


2 strands bonded together by base pairs that are bonded byhydrogen bonds



Nucleotides are the building blocks of DNA. DNA nucelotides are made up of
1. Deoxyribose Sugar
2. A Nitrogen Base (C,G,A or T)
3. Phosphate Group

Appendix 4: Student Resources: Note Summaries



DNA strands

DNA wrapped around proteins to form **Nucleosome**

Chromosome

we never see a **chromosome** like this because the only time we see the genetic material condesned like this is during cell division and during cell division the DNA has already been replicated. Hence we see the 2 sister chromatids.
Note: This means that in Karyograms, we see the chromosome in replicated form as well (sine it is condensed)

instead we see it like this

Chromatin-
How DNA exists in G1

Replicated Chromatin-
How DNA exists in after S phase in Interphase

condenses at the first phase of nuclur division (meoisis/mitosis)

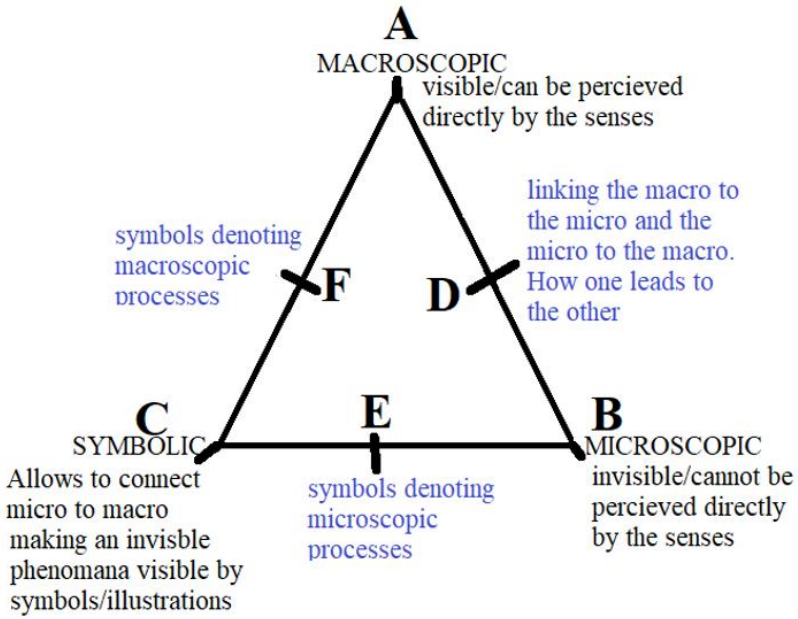
2 Sister chromatis-
the replicated chromatin that has condensed to enter cell division. Are exact copies of one another

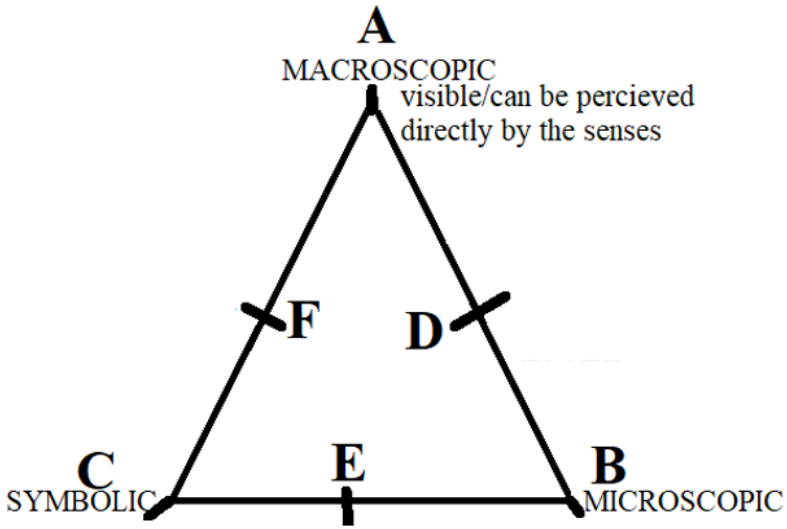
Appendix 5: Student Resources: Supplementary Unit Sheet for 3.1

Content	Term/ concept	IB Definition	Is it macro/ micro/ symbolic. **Justify**	**What is it? (a process? A molecule?** Is it something that physically exists?**)**	**Purpose/Role /Use**	Sketch
2.6	DNA					
2.6	DNA "bases"/ Nucleotides					
1.6	Chromatin					
1.6	Sister Chromatids					
1.6	Mitosis					
2.7	DNA Replication					
2.7	Protein Synthesis					
2.7	Transcription					
2.7	Translation					
2.7	Codon					
2.7	mRNA					
2.4	Amino acid					
3.1 and 1.6	Chromosome					
3.1	Genome					
3.1	Genotype					
3.1	Phenotype					
3.1	Gene					
3.1	Allele					
3.1	Locus					
3.1	Mutation					

Appendix 6: Student Resources: Triangle Template for Concept

[Concept Title]





Appendix 7:
Sample Questions from the Genetic Literacy Assessment Items (GLAI)

8. An individual is found to have a mutation in a gene associated with breast cancer. In which cells is this form of the gene located?
a. Only in cells of the breast where cancer occurred.
b. Only in cells of both breasts.
c. Only in those cells found in females.
d. Only in the cells of the breast and ovaries.
e. All the cells of the individual.

9. Mutations in DNA occur in the genomes of most organisms, including humans. What is the most
important result of these mutations?
a. They produce new genes for the individual.
b. They produce new enzymes for the individual.
c. They provide a source of new cells for the individual.
d. They provide a fundamental source of genetic variation for future generations.
e. They produce new chromosomes for future generations.

10. Multiple genes are associated with complex diseases such as cancer and mental disorders. When an individual is tested for these genes, what do the results indicate?
a. Whether or not s/he has the disease or disorder.
b. Whether or not s/he has an increased risk for developing the disease or disorder.
c. Whether or not s/he will definitely develop the disease or disorder.
d. Whether or not his/her children will definitely develop the disease or disorder.
e. How severe the disease or disorder will be if the individual has the gene.

11. Which of the following is a current benefit of the application of genetics and genetic technology to health care?
a. The ability to significantly increase human life expectancy.
b. The ability to conquer complex diseases like cancer.
c. The creation of inexpensive and easily administered drugs.
d. The ability to identify individuals and groups who are at increased risk of disease.
e. The ability to routinely use gene therapy to cure genetic diseases.

17. Huntington's disease is a genetic disorder caused by a dominant gene. Symptoms begin in adulthood and the disease is ultimately fatal. What is an ethical dilemma presented by Huntington's disease when a parent is diagnosed with the disease?
a. Whether that parent should be tested for the gene.
b. Whether the other parent should be tested for the gene.
c. Whether and when any of the children should be tested for the gene.
d. Whether the parent should be treated for the disease.
e. Whether that parent should be told s/he has Huntington's disease.

Appendix 8:
Concepts Addressed by the Genetic Literacy Assessment Items (GLAI)

I. NATURE OF THE GENETIC MATERIAL.

Ia. DNA is the genetic material of virtually all different types of organisms. [5,13]

Ib. Occasional errors in DNA structure and replication result in genetic variation. [9, 15]

Ic. DNA is organized into cellular structures called chromosomes. Genes are segments of' DNA within chromosomes. [1, 16]

Id. virtually all cells within an individual contain the same genetic constitution- Different cells and tissues are produced through differential gene activity. [8, 22]

II. TRANSMISSION

IIa. Chromosome number is reduced by half during meiosis, which results in the formation of genetically different gametes. [6, 30]

IIb. Understanding Mendelian patterns of inheritance, and their biological basis, allows probability statements about the occurrence of traits in offspring. [7, 28]

III. GENE EXPRESSION

IIIa. Many genes code for proteins, which in turn produce individual traits. [4, 25]

IIIb. The functions of a gene and its protein product can be affected by the environment at one or many steps involved in producing a given trait. [21, 23]

IIIc. Most human traits, including diseases, result from the products of multiple genes interacting with environmental variables: examples include height, heart disease, cancer, and bipolar disorder. [3, 18]

IV. GENE REGULATION

IVa. Some genetic variation results in disease in virtually every environment, for example, the mutations associated with Huntington disease, Tay-Sachs disease, and cystic fibrosis. [20]

IVb. There are other genetic variations that result in disease less consistently, for example, the BRCA1 mutation associated with breast cancer. [10,12]

IVc. Much of gene regulation involves turning genes on and off at the right time. [19]

V. EVOLUTION

Va. Genetic variation is the rule rather than the exception in the living world, and is the basis for evolution by natural selection: without genetic variation there can be no differential selection, and no survival of any species. [14, 26]

Vb. Genetic variation is much greater within traditional human ethnic groups than among them. Superficial phenotypic differences do not reflect the high degree of genetic relatedness among traditional ethnic groups [24]

VI. GENETICS & SOCIETY

VIa. The current and future application of genetics and genetic technology to such areas as health care, forensic analysis, genetically modified organisms, etc. holds great potential for improving life.[2, 11]

VIb. Like all technologies, genetic technologies are fallible and have unintended consequences, some of which can be harmful to individuals, families. or groups. [17,30]

VIc. Science often can tell us what we can or cannot do, but it does not always indicate clearly what we should do. Those decisions arise from the intersection of science with ethics, the law. and public policy. [27, 29]

Appendix 9:
Sample Questions from the Two-Tier Questionnaire

Selected Items from the two-tier diagnostic instrument for genetics developed by Chi-Yan Tsui & David Treagust (2009).

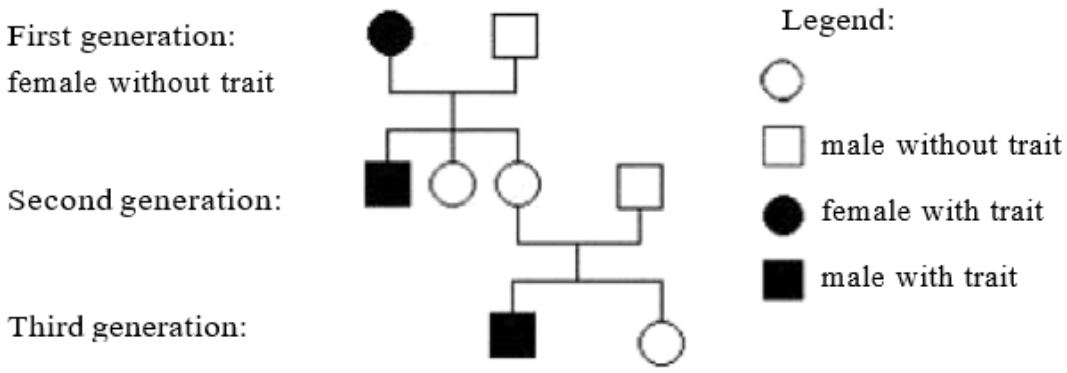
Item 1

The trait, curly hair, is dominant to straight hair. If we use "C" to represent the dominant allele (gene) for curly hair and "c" for the recessive allele, would a person with genotype Cc have curly hair?
[ ] 1. Yes
[ ] 2. No
[ ] 3. Don't know

Reason for the above:
[ ] 1. The person needs to have CC for curly hair.
[ ] 2. The dominant allele C is expressed in a Cc condition.
[ ] 3. The person may or may not have curly hair.
[ ] 4. The recessive allele c is expressed.

Item 3

Which of the following best describes the trait in the following pedigree?



[ ] 1. Recessive
[] 2. Dominant
[ ] 3. Cannot tell
[ ] 4. Don't know

Reason for the above:
[ ] 1. Only one of the three children in the second generation has the trait.
[ ] 2. Both the female in the first generation and her son have the trait.
[ ] 3. One male in third generation has the trait but his parents do not have it.
[ ] 4. The trait can be either recessive or dominant.

Appendix 10:
Types of Genetics Reasoning Identified in the Two-Tier Questionnaire

6 Six types of genetics reasoning, adapted from Tsui & Treagust (2009 *p.1077)*

		Domain-general dimension of reasoning (Novice ◄——► Expert)		
		Cause-to-effect reasoning	Effect-to-cause reasoning	Process reasoning
Domain-specific dimension of reasoning (simple ←→ complex)	Between-generations	Monohybrid inheritance: Mapping genotype to phenotype (Type II)	Monohybrid inheritance: Mapping phenotype to genotype (Type IV)	Punnett squares (input/output reasoning): Meiosis process (event reasoning) Mitosis process[a] (Type VI)
	Within-generations	Mapping genotype to phenotype (Type I)	Mapping phenotype to genotype (Type III)	Mapping information in DNA base sequence (genotype) to amino acid sequence in protein synthesis (phenotype)[b] (Type V)

Appendix 11:
Sample Interview Questions

Interview 1 - Main/Focal Questions

1. **How would you define DNA?**
2. **How would you define chromosomes?**
3. **How would you define genes?**
4. **If you're given a super microscope and you're told to find a gene, where would you zoom in and how would you know if it is a gene or not**
5. **Do all cells have the same genes**
6. **What is genetic material made up of**

Interview 4 - Main/Focal Questions

1. **What is the difference between genotype and phenotype?**
2. **What is the difference between a chromosomal disorder and a genetic mutation? How do they compare in regard to modes of inheritance?**
3. **how is the sex of the offspring determined?**
4. **Why do we look like our parents, what processes that happen microscopically, make us look like our parents?**
5. **Organize the concept of [down-syndrome/sex determination] within the triangle scheme**

Appendix 12:
Sample Extended-Response Questions

ERQ Sequence	Question
1	How does a gene for a particular trait actually make that trait happen? For example, how does a gene for dimples make the individual end up having them.
2	Each type of species has their distinct chromosome number. Humans have a chromosome number of 46, while chimpanzees have a number of 48. If I somehow managed to successfully add 2 pairs of chromosomes to a human stem cell so that it will have 48 chromosomes, what do you think will happen? will this cell develop into a chimpanzee cell? why or why not?
3	What is meant by the genetic code is universal? explain how the genetic code is universal.
4	In your own words, explain how Genetically Modified Organisms (GMOs) are produced, such as insulin producing bacteria.

Appendix 13:
The Genetics Project

Name: Date:
IB Biology Chapter 3: Project

In this project, you will be receiving 2 sets of chromosomes, the first set will belong to a female human, and the second will belong to a male human.
You will be using those chromosomes to show how they interact in different parts of the cell cycle of a diploid and a haploid cell.
You will first cut the chromosomes for both the male and female, then you will arrange the chromosomes to match the required scenario under each section of the report. Note that you will **not** actual **paste/glue** the chromosomes as you will need to re-use them for consecutive parts. Instead, you will arrange them in the required order, take pictures. Those pictures you will **paste** as a report which you will submit as part of your final product.
Your final product will also include a sketch of an offspring that is a combination of both the female and male chromosome based on the results you get. This will be clarified in the requirements.
This project report is due on **March 1st, and you will be given one class to work on it.** This will count as a project grade out of 50 points.

Male/Paternal: ♂

Female/Maternal: ♀

Instructions:

1. Take a picture of the female and male chromosomes before cutting them so you have a reference picture in case you lose track of chromosome number.
2. Fill out the table for the male and female (chromosome/allele/trait) to get the phenotype of the male and female
3. Cut the female and male chromosomes.
4. Arrange each set to show how a karyogram of each would look like. Take a picture to paste later in your part
5. Take an A4 paper and draw a big cell in it. Arrange the chromosomes for **each** in this cell according to the requirements below (#2 onwards).
6. Once you have the chromosomes for the offspring, fill out the table (chromosome/allele/trait) to get the phenotype of the offspring (from #7)
7. Make sure the chromosomes are labeled as sister chromatids, homologous chromosomes
8. Make sure the cells are labeled as diploid or haploid

Grading will be based on the following:

1. All requirements have been met– 25 points
2. The requirements have been represented accurately- 10 points
3. For requirement #8, the sketch of the offspring is clear and reflects accurately the alleles – 5 points

4. Work is submitted on time as a hard copy at the beginning of class on the 19th – 5 points
5. Work is neat and organized 5 points

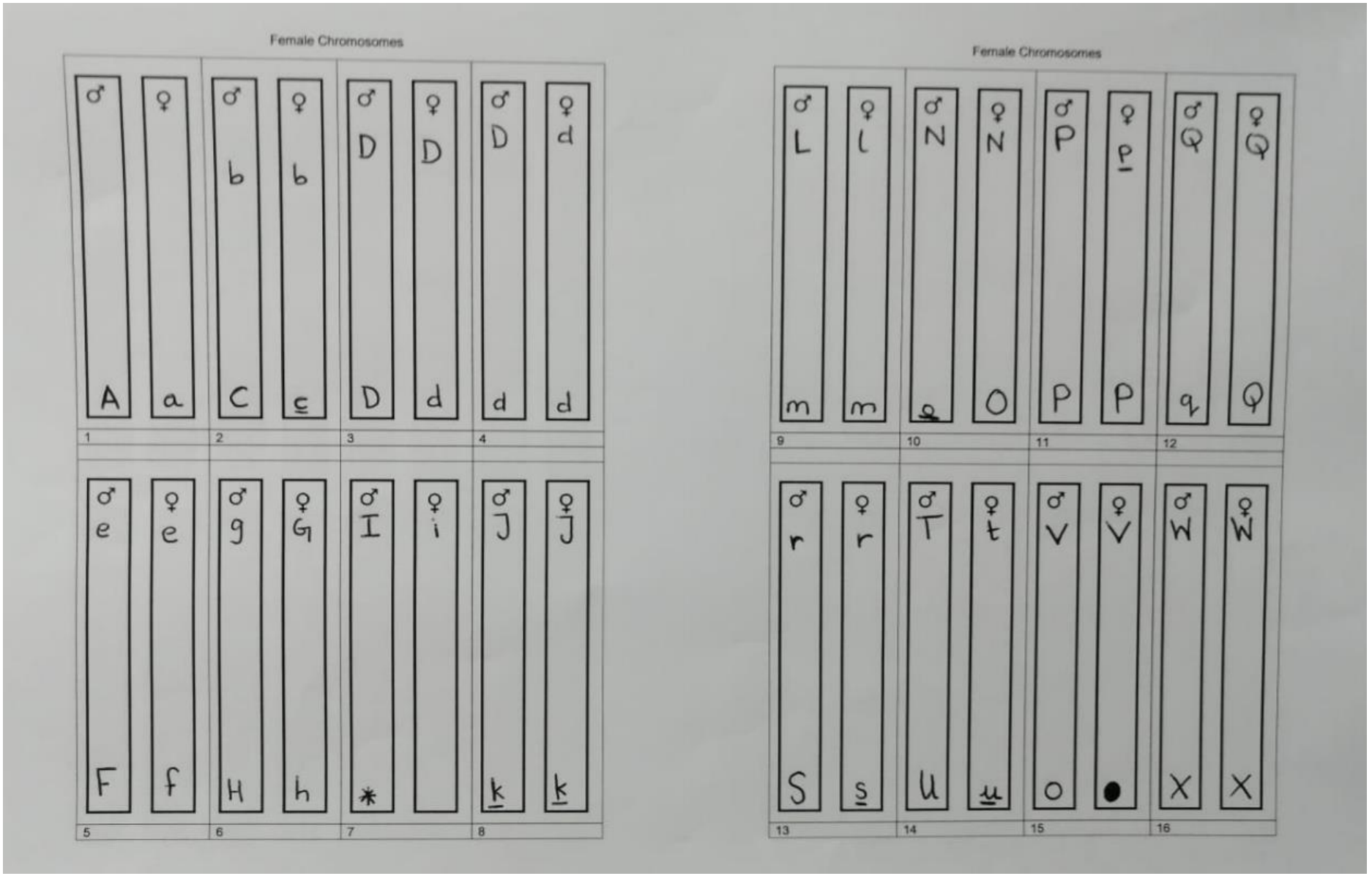
Summary of requirements in report

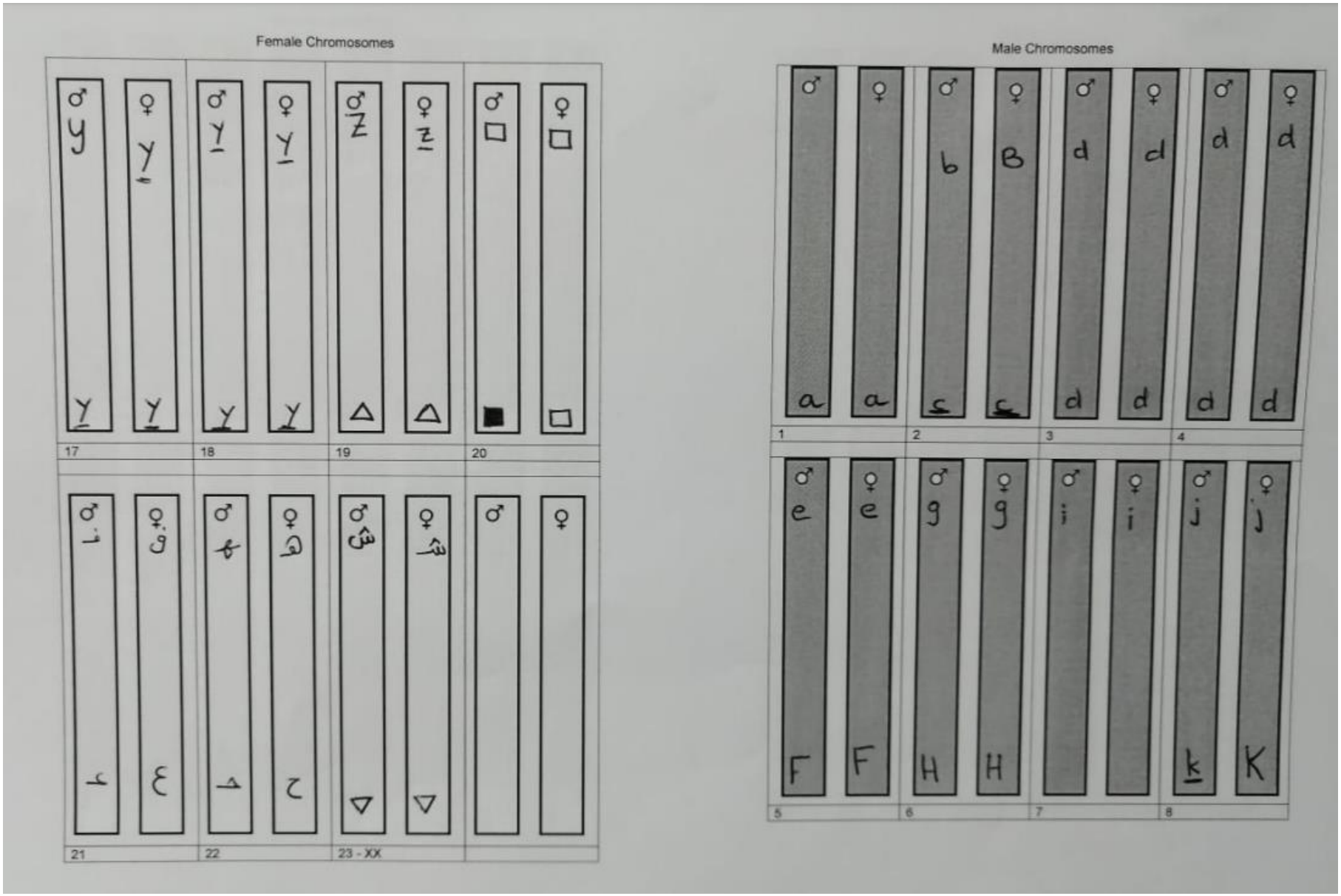
1. Karyogram
    a. Of male
    b. Of female
2. Mitosis of male
        i. Prophase
        ii. Metaphase
        iii. Anaphase
        iv. Telophase
1. Mitosis of female
        i. Prophase
        ii. Metaphase
        iii. Anaphase
        iv. telophase
2. Meiosis of male
        i. Prophase I- before crossing over. Make sure you form at least one chiasma on 10 homologues.
        ii. Prophase I- after crossing over
        iii. Metaphase I
        iv. Anaphase I
        v. Telophase I
        vi. Prophase II
        vii. Metaphase II
        viii. Anaphase II
        ix. Telophase II
3. Meiosis of male
        i. Prophase I- before crossing over. Make sure you form at least one chiasma on 10 homologues.
        ii. Prophase I- after crossing over
        iii. Metaphase I
        iv. Anaphase I
        v. Telophase I
        vi. Prophase II
        vii. Metaphase II
        viii. Anaphase II
        ix. Telophase II

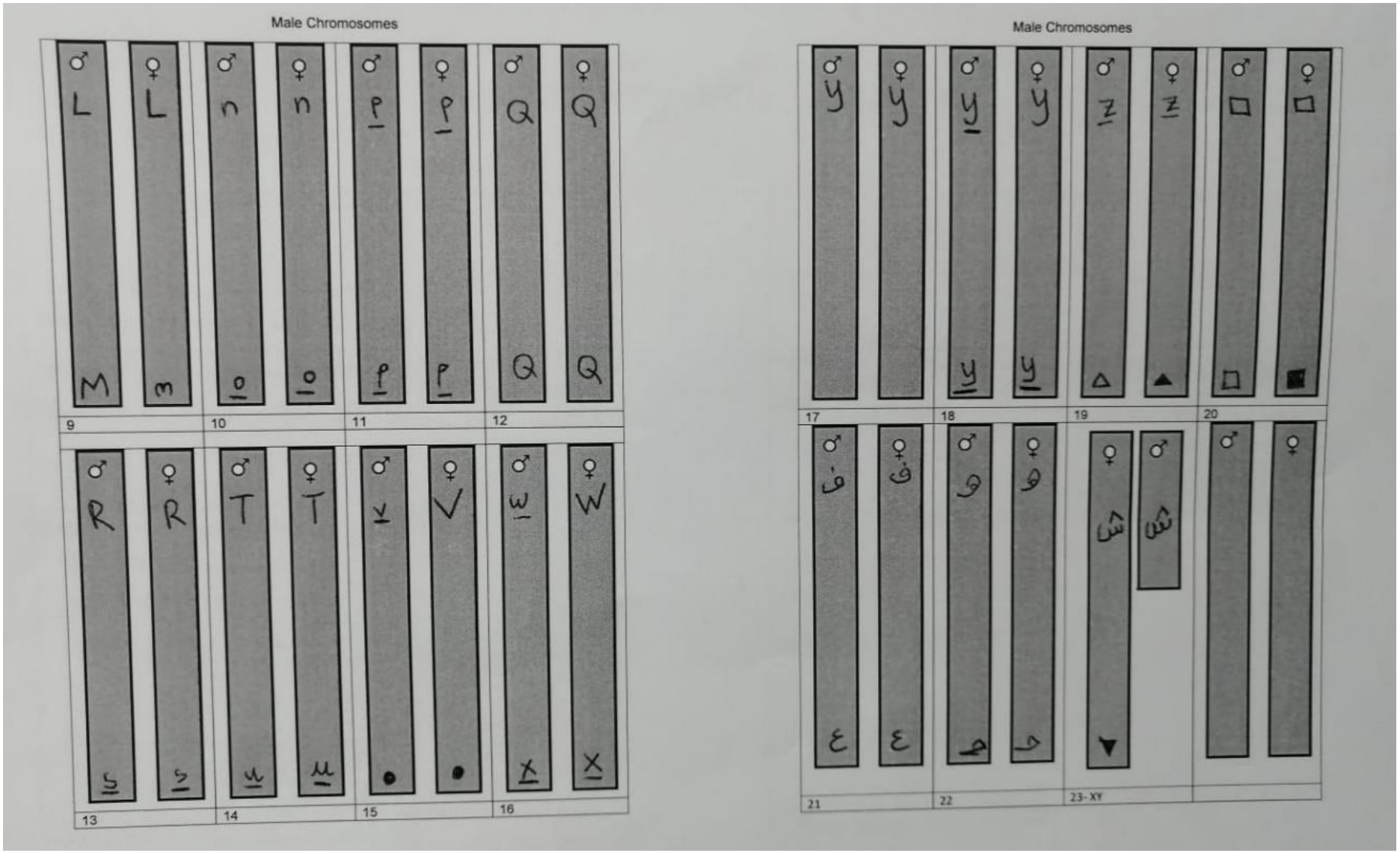
4. Choose either male or female chromosomes and show non-disjunction during meiosis. Non-disjunction can occur in either the first or second meiotic division. Make sure to include all stages of meiosis:
        i. Prophase I- before crossing over. Make sure you form at least one chiasma on 10 homologues.
        ii. Prophase I- after crossing over
        iii. Metaphase I
        iv. Anaphase I

v. Telophase I
vi. Prophase II
vii. Metaphase II
viii. Anaphase II
ix. Telophase II

5. Take one cell product from meiosis of the male and female (#4 and 5) and fuse them to show the process of fertilization. Show the karyogram of the resulting cell.
6. Use the symbols on the chromosomes of the zygote to sketch how the offspring would look like based on the allele/trait table.


Female Chromosomes
♂ A
♀ a
1
♂ b
♀ b
C c
2
♂ D
♀ D
D d
3
♂ D
♀ d
d d
4
♂ e
♀ e
F f
5
♂ g
♀ g
H h
6
♂ I
♀ i
*
7
♂ J
♀ J
k k
8
Female Chromosomes
♂ L
♀ l
m m
9
♂ N
♀ N
n O
10
♂ P
♀ P
P P
11
♂ Q
♀ Q
q Q
12
♂ r
♀ r
S s
13
♂ T
♀ t
U u
14
♂ V
♀ V
O ●
15
♂ W
♀ W
X X
16


Female Chromosomes
17
18
19
20
21
22
23 - XX
Male Chromosomes
1
2
3
4
5
6
7
8


Male Chromosomes
Male Chromosomes
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23- XY

KEY

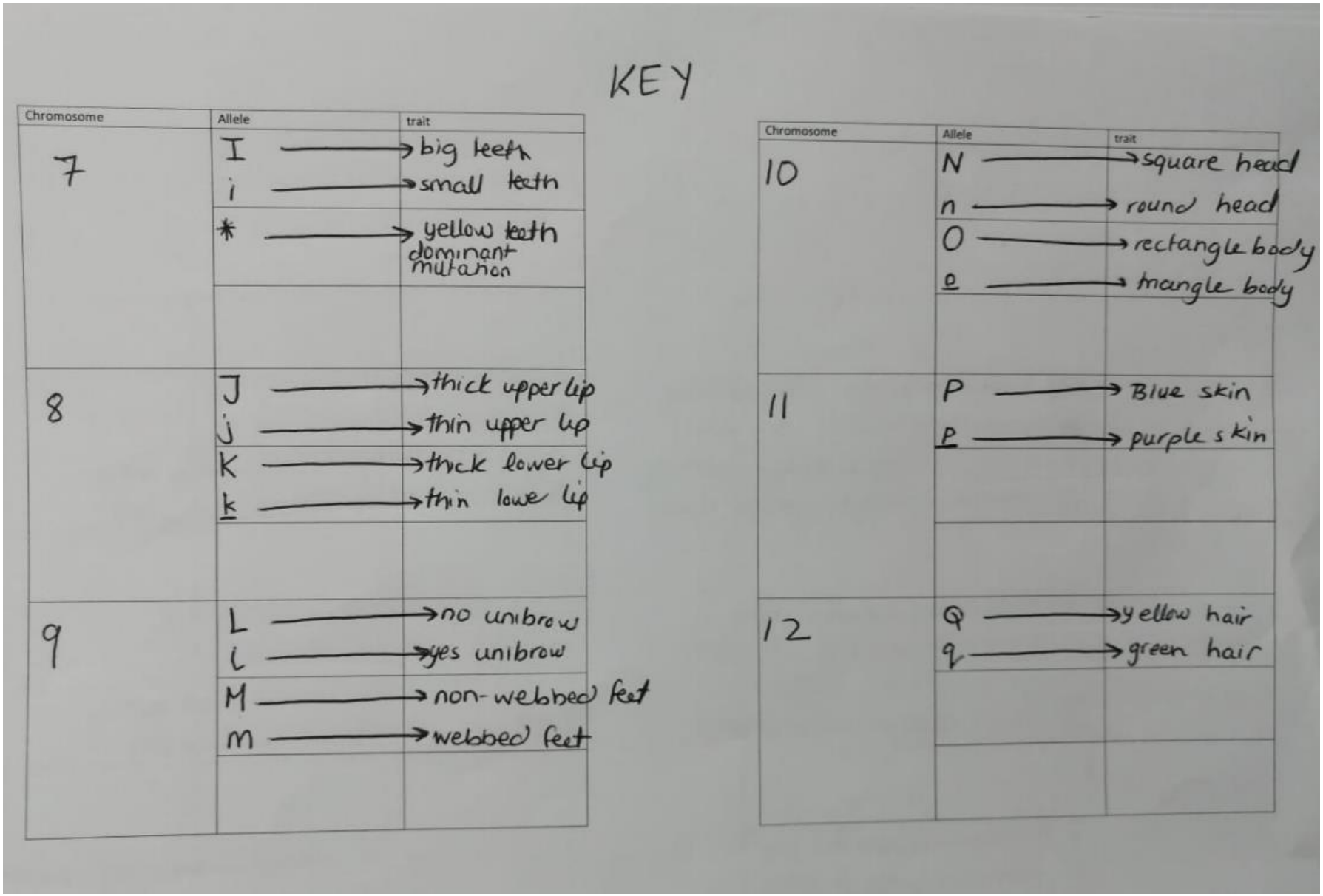
Chromosome	Allele	trait
1	A	→ big ears
	a	→ small ears
2	B	→ thick eyebrows
	b	→ thin eyebrows
	C	→ cleft chin
	c	→ no cleft chin
3	D	→ dark pigment for eyes
	d	→ light pigment for eyes

Chromosome	Allele	trait
4	D	→ Dark pigment for eyes
	d	→ light pigment
5	E	→ round nose
	e	→ sharp nose
	F	→ big nostrils
	f	→ small nostrils
6	G	→ long eyelashes
	g	→ no eyelashes
	H	→ no freckles
	h	→ freckles

* Capital letter over / allele dominant lowercase

* colored shape dominant over empty

* arabic letters codominant


KEY
Chromosome
Allele
trait
7
I → big teeth
i → small teeth
* → yellow teeth dominant mutation
8
J → thick upper lip
j → thin upper lip
K → thick lower lip
k → thin lowe lip
9
L → no unibrow
l → yes unibrow
M → non-webbed feet
m → webbed feet
10
N → square head
n → round head
O → rectangle body
o → mangle body
11
P → Blue skin
p → purple skin
12
Q → yellow hair
q → green hair

KEY

Chromosome	Allele	trait
13	R	cat tail
	r	no cat tail
	S	curly hair
	s	straight hair
14	T	no cat whiskers
	t	cat whiskers
	U	teddy bear eyes
	u	human eyes
15	V	equal-length arms
	v	arm length inequal
	●	equal size eyes
	O	eye size inequal

Chromosome	Allele	trait
16	W	big feet
	w	small feet
	X	big hands
	x	small hands
17	y	tall
	y	short
18	y	tall
	y	short

Appendix 14: Sample

Teacher Reflections

Lesson Plan 1: Teacher Reflection

Today was the first day filming in class, and I felt that both the students and I were tense because of that. Because of the camera, I subconsciously restricted my movement in the class-room and remained near my desk rather than walk around like I usually do. This also influenced how much I used/wrote on the white board. I think what was difficult for me was not the presence of the camera, but rather the fact that I will be watching myself later, it made me very apprehensive. I also feel that my anxiety/apprehensiveness was reflected on the students, and that if I were to be more relaxed, it would reflect positively on the students. In general, the class-room atmosphere did not feel very natural.

The aim of the lesson today was to introduce the topic of genetics, spike the students' interest, and introduce the concept of micro/macro and symbolic representations at the same time. I focused the lesson on superheroes and how superheroes are made through mutation, and whether such events are possible. I then guided the students into the process of evaluating the idea of the superhero, by giving background information on our genome, current genetic engineering technologies and so on. I felt relatively positive regarding introducing the unit in this lesson.

1. *Weaknesses:*

I felt the lesson was very teacher-centered in the sense that there was very little student interaction and it was mostly lecturing or listening passively. I think the student would significantly improve if I were to make the activity of "create your own super-hero" as a worksheet that students can work on and fill throughout the discussion and submit at the end of class. This is so that I can ensure that all students are engaging one way or another.

Furthermore, I was also concerned that I introduced too many terms without providing much context for each and hence this is something I need to revisit in the next lessons and re-emphasize.

Another aspect which could use improvement is when playing a video, I should have a handout that students fill or guided notes they can take so the video will turn into time to lose focus.

1. *Strengths:*

I felt that the activity of creating the superhero was a good way of introducing the microscopic, macroscopic and symbolic terminologies in a familiar context, and it fit well with the topic. Linking the outcome/super-power to macro, and the code to do so to the micro and simultaneously using this activity as a way to introduce the human genome project and its significance was a good way to start the unit.*:*

Appendix 14: Sample Teacher Reflections

Lesson Plan 4: Teacher Reflection

In today's class, we did two think-focused strategies, including constructing a concept map, and an exercise of "see, think, wonder" (STW) . The concept map exercise was meant to re-cap some of the students' knowledge on genetic related terms, by including terms of varying familiarity. The STW exercise was meant to introduce the new content to the students using visual representations (graphs) and prompt their interest by making them come up with questions that are meant to be addressed in the lesson later.

1. *Weaknesses:*

I think it would have made the lesson more useful, particularly the concept map exercise, if after they submitted their work, I demonstrated how to do it on the board. I believe that by not doing that, I missed out on a learning opportunity.

1. *Strengths:*

The STW was a good exercise to engage the students in thinking about words such as "genome", "diploid number "and "gene number", which are all somewhat abstract, and try to form a connection between those values and the organism they represent. There were some discrepancies between student expectations of these values, and the actual data on the bar graphs. These discrepancies were solved by reflecting on the meaning of those terms and values and what they actually represent. This was particularly true when relating genome size, gene number and diploid number to organism complexity. A lot of the students initially thought that humans, as most complex organisms should have the highest values for all, but when that was not noted, the class indulged in a discussion of how higher values for these terms might not necessarily reflect complexity. We also discussed what other information we might need to get more insight on the organism's complexity. There were also comparisons prompted regarding the values for gene number and genome size and how can an organism have a higher genome number whilst having a lower genome size compared to another organism. These comparisons allowed the students to delve more into the ontological aspect of the terms.

Furthermore, because we were linking these values to the orgasm as a whole and then comparing these values across organisms, there was also the multiple representation factor included. I did not explicitly use the triangle in this lesson; however, students were exposed to microscopic and macroscopic representations implicitly which still serves the purpose.

Appendix 14: Sample
Teacher Reflections

Lesson Plan 7: Teacher Reflection

Today, I start the lesson with an activity. The students were shown simplified pictures of meiosis (all 8 steps) and then asked to use these pictures, and their prior knowledge to describe what is happening at every step. This allowed the students to link the symbolic- what is represented in the picture- to the microscopic which is the steps represented in the images.

It was evident through the class discussion that students were challenged by the idea of haploid vs diploid throughout the process of meiosis.

1. *Weaknesses:*

The wrap up activity was a great tool to recap the main ideas but it was rushed due to time constraints.

Furthermore, I should have more supporting/visual aids to support the explanation of haploid vs diploid as it was clear that students faced difficulty in understanding those.

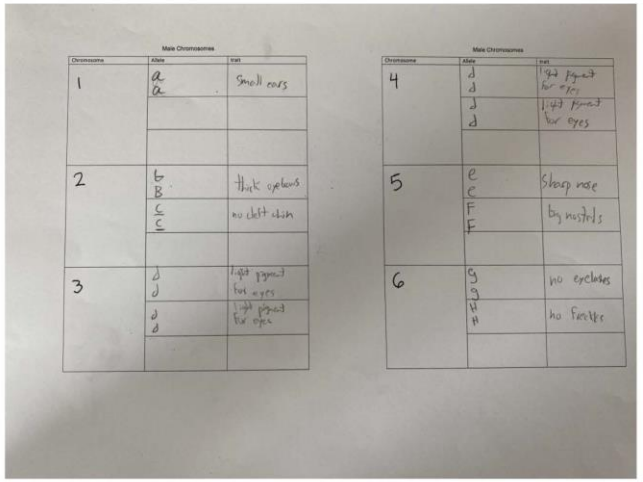
1. *Strengths:*

At the beginning of the activity there were guiding questions, and throughout the activity, there were questions prompting the student to link the images of meiosis to the DNA concepts studied in earlier sections, such as, “how many chromosomes are shown in the image, how many homologous chromosomes? Sister chromatids...?”. These questions helped the students link the concepts together, the microscopic and the symbolic.

Furthermore, the students were engaged in writing their own observations at first, then adding to those. They were diligent in writing notes and contributing once they found out I was going to collect their work at the end of class.

Appendix 15: Student Samples
Appendix 15A: Student Project Samples

Male alleles & traits tables

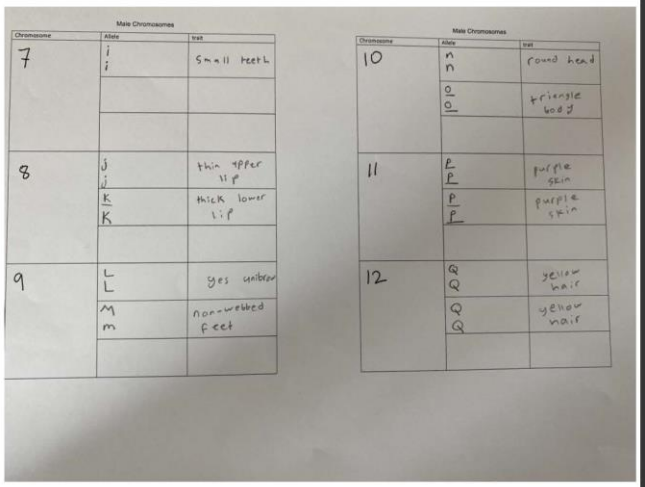


Male Chromosomes

Chromosome	Allele	trait
1	a a	Small ears
2	b B	thick eyebrows
	c c	no cleft chin
3	d d	light pigment for eyes
	d d	light pigment for eyes

Male Chromosomes

Chromosome	Allele	trait
4	d d	light pigment for eyes
	d d	light pigment for eyes
5	e e	Steep nose
	F F	big nostrils
6	g g	no eyelashes
	H H	no freckles

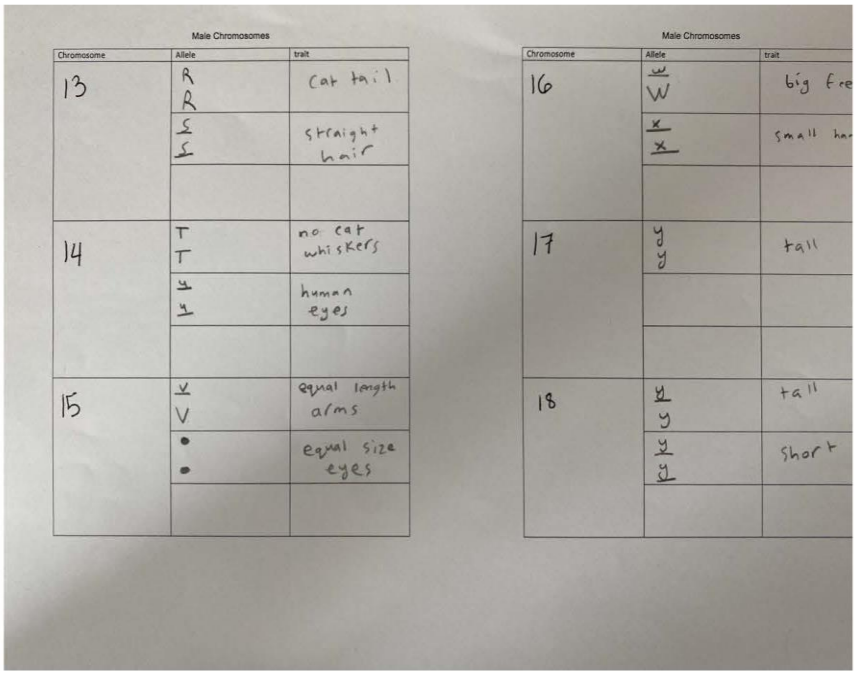


Male Chromosomes

Chromosome	Allele	trait
7	i i	Small teeth
8	j j	thin upper lip
	K K	thick lower lip
9	L L	yes unibrow
	m m	non-webbed feet

Male Chromosomes

Chromosome	Allele	trait
10	n n	round head
	o o	triangle body
11	P P	purple skin
	P P	purple skin
12	Q Q	yellow hair
	Q Q	yellow hair

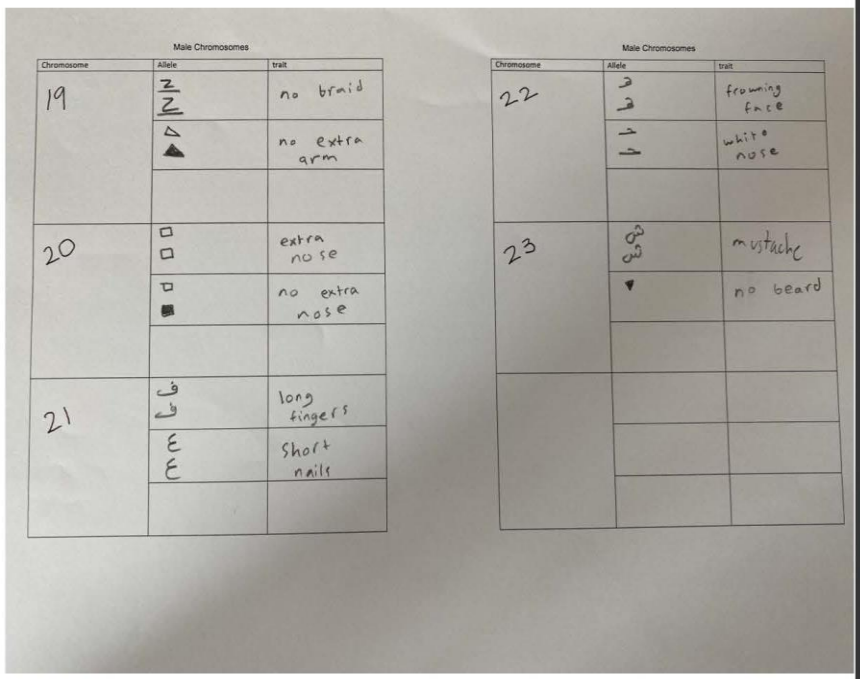


Male Chromosomes

Chromosome	Allele	trait
13	R R	cat tail
	S S	straight hair
14	T T	no cat whiskers
	Y Y	human eyes
15	V V	equal length arms
	● ●	equal size eyes

Male Chromosomes

Chromosome	Allele	trait
16	W W	big fre
	X X	small ha
17	Y Y	tall
18	Y Y	tall
	Y Y	short

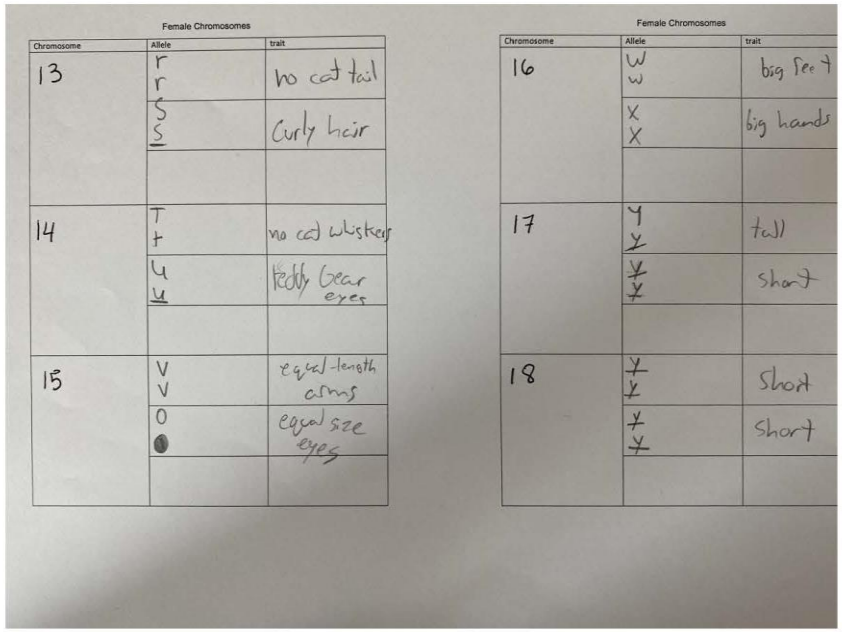


Male Chromosomes

Chromosome	Allele	trait
19	Z Z	no braid
	△ ▲	no extra arm
20	□ □	extra nose
	□ ■	no extra nose
21	ف ف	long fingers
	ع ع	short nails

Male Chromosomes

Chromosome	Allele	trait
22	ق ق	frowning face
	ـ ـ	white nose
23	ش ش	mustache
	▼	no beard

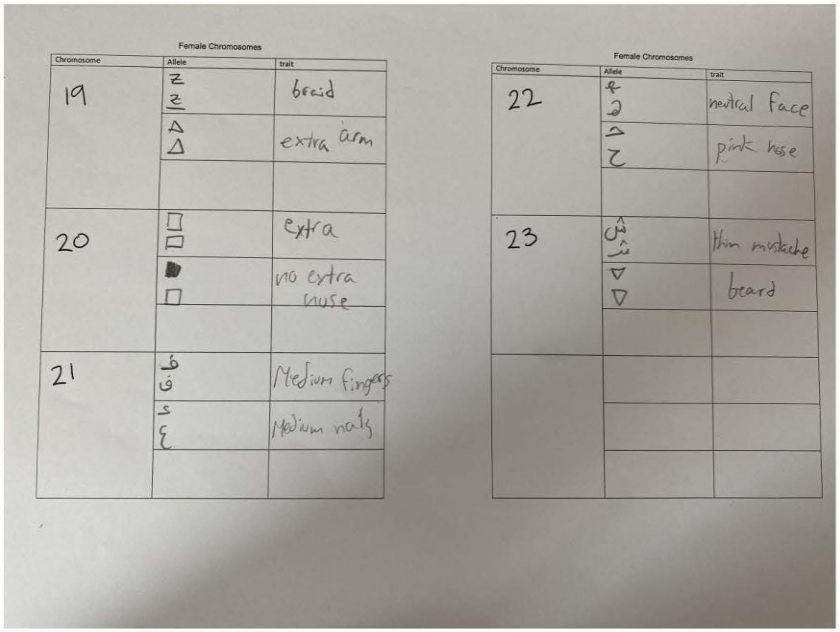


Female Chromosomes

Chromosome	Allele	trait
13	r r	no cat tail
	S S	Curly hair
14	T T	no cat whiskers
	Y Y	Teddy Bear eyes
15	V V	equal-length arms
	O ●	equal size eyes

Female Chromosomes

Chromosome	Allele	trait
16	W W	big feet
	X X	big hands
17	Y Y	tall
	Y Y	short
18	Y Y	short
	Y Y	short



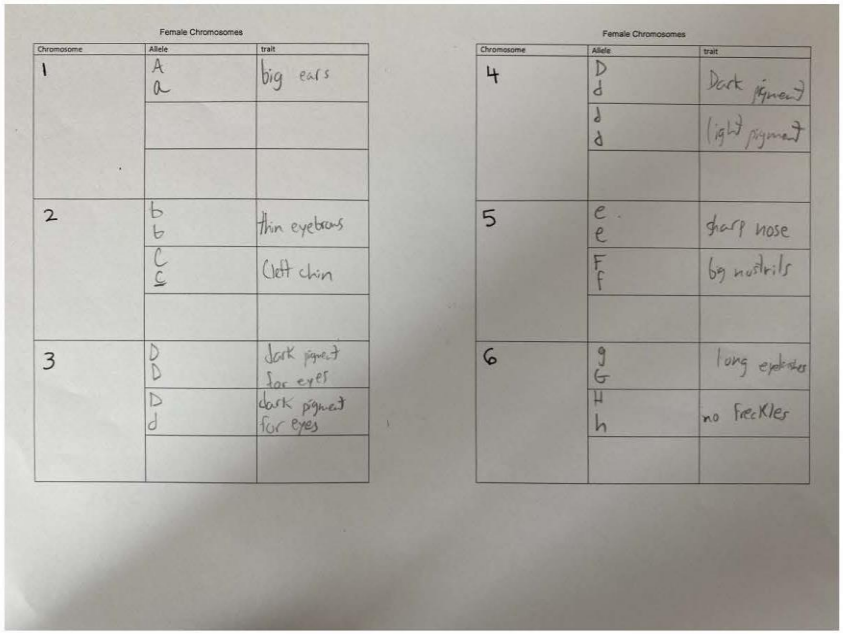
Female Chromosomes

Chromosome	Allele	trait
19	Z Z	braid
	Δ Δ	extra arm
20	□ □	extra
	■ □	no extra nose
21	ف ف	Medium fingers
	ع ع	Medium nails

Female Chromosomes

Chromosome	Allele	trait
22	ع ع	neutral face
	∩ ∩	pink nose
23	ش ش	thin mustache
	▽ ▽	beard

Female alleles & traits tables

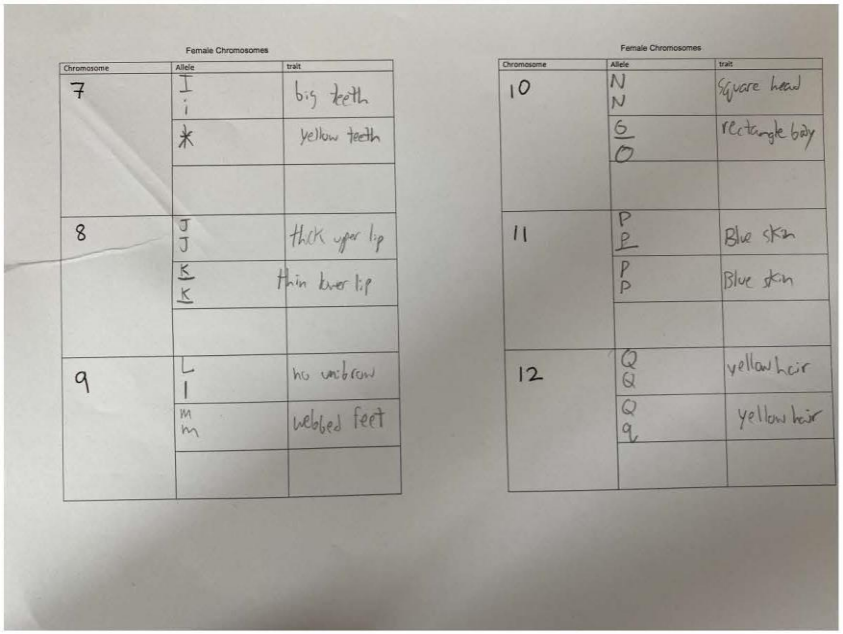


Female Chromosomes

Chromosome	Allele	trait
1	A a	big ears
2	b b	thin eyebrows
	C c	Cleft chin
3	D D	dark pigment for eyes
	D d	dark pigment for eyes

Female Chromosomes

Chromosome	Allele	trait
4	D d	Dark pigment
	d d	light pigment
5	e e	sharp nose
	F f	big nostrils
6	g G	long eyelashes
	H h	no freckles



Female Chromosomes

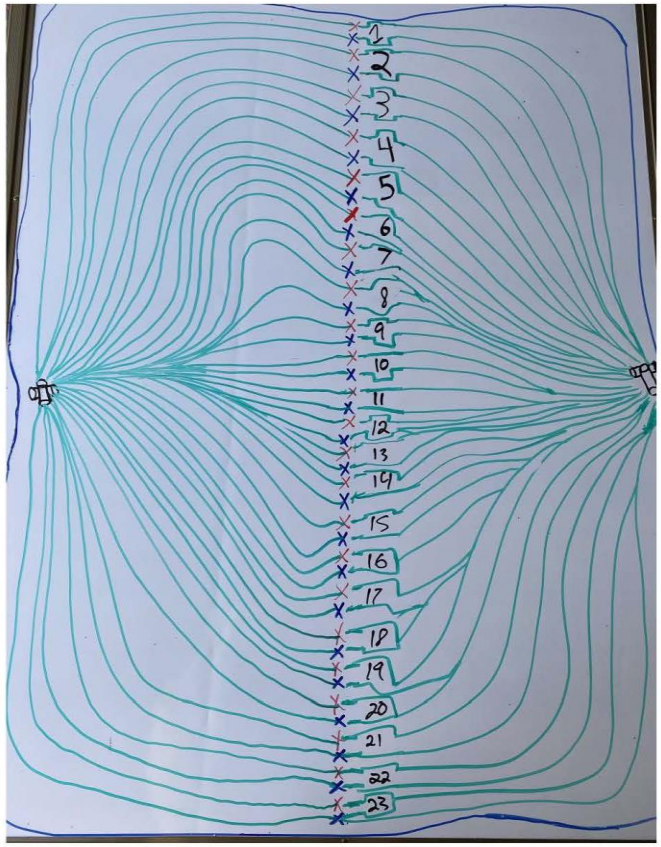
Chromosome	Allele	trait
7	I i	big teeth
	*	yellow teeth
8	J J	thick upper lip
	K K	thin lower lip
9	L l	no unibrow
	M m	webbed feet

Female Chromosomes

Chromosome	Allele	trait
10	N N	Square head
	O O	rectangle baby
11	P P	Blue skin
	P P	Blue skin
12	Q Q	yellow hair
	Q q	yellow hair

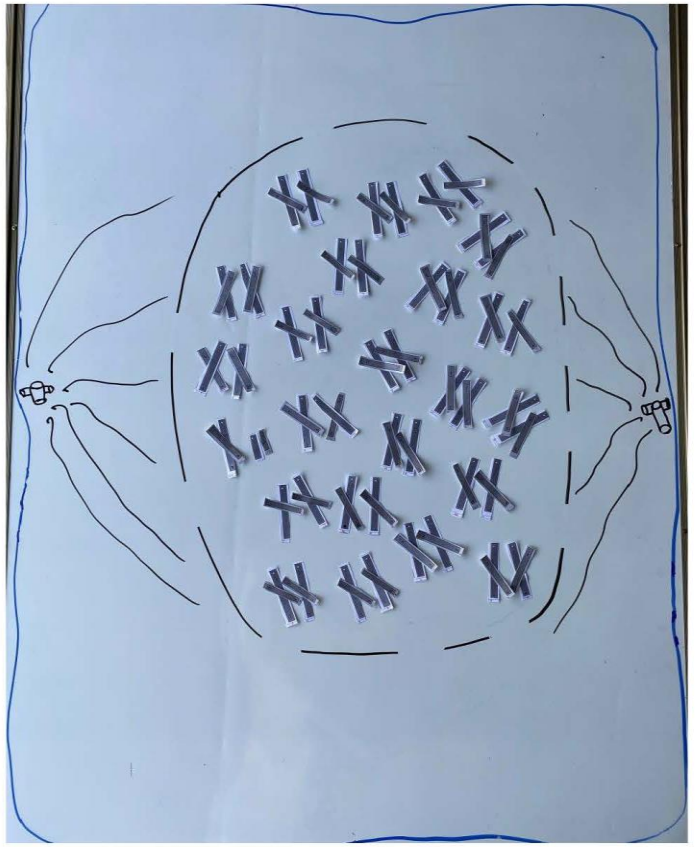
Mitosis(Male) Metaphase (*2n*)

- Chromosomes line up along equator of cell
- Spindles attach to each chromosome
- Red are maternal and blue are paternal chromosomes



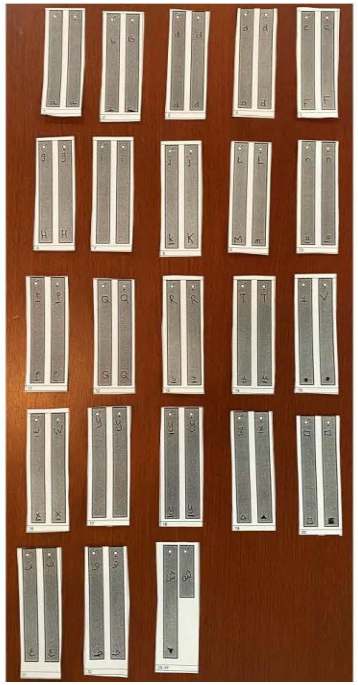
2) Mitosis(Male) Prophase (*2n*)

- Chromatin condenses into chromosomes (sister chromatids)
- The nuclear envelope breaks down
- Centrioles move to poles
- Spindle fibers start to form

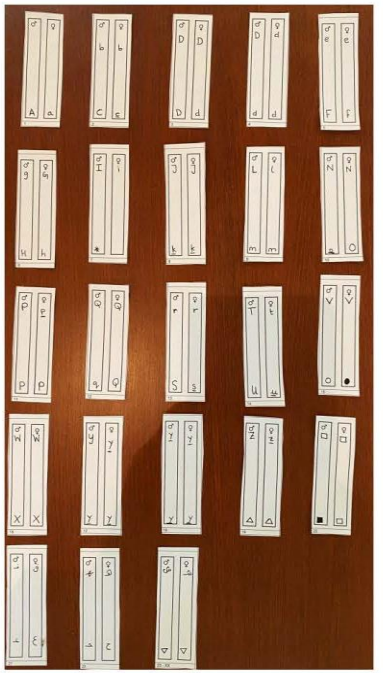


1) Karyogram

Male

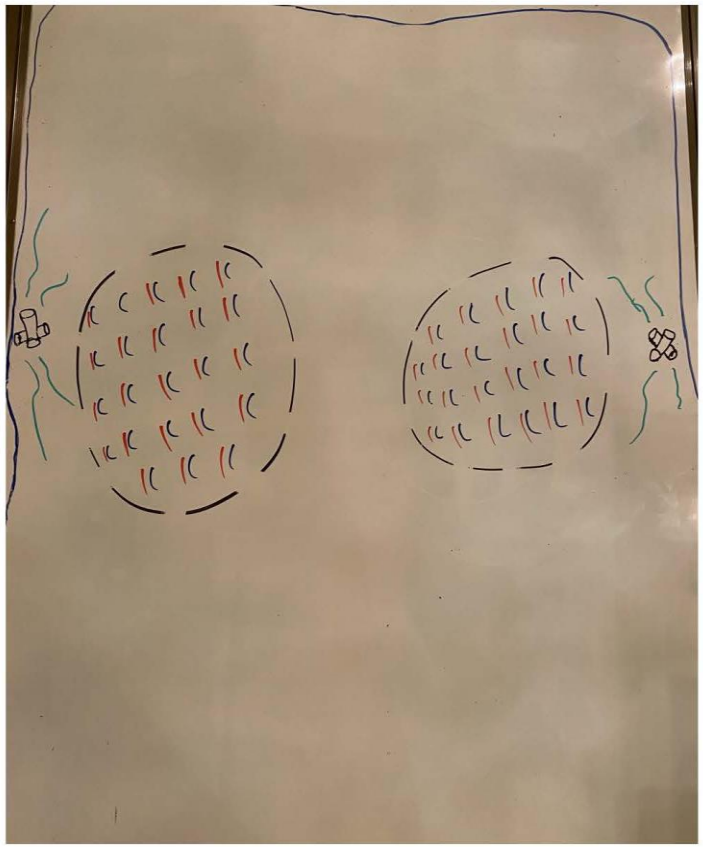


Female



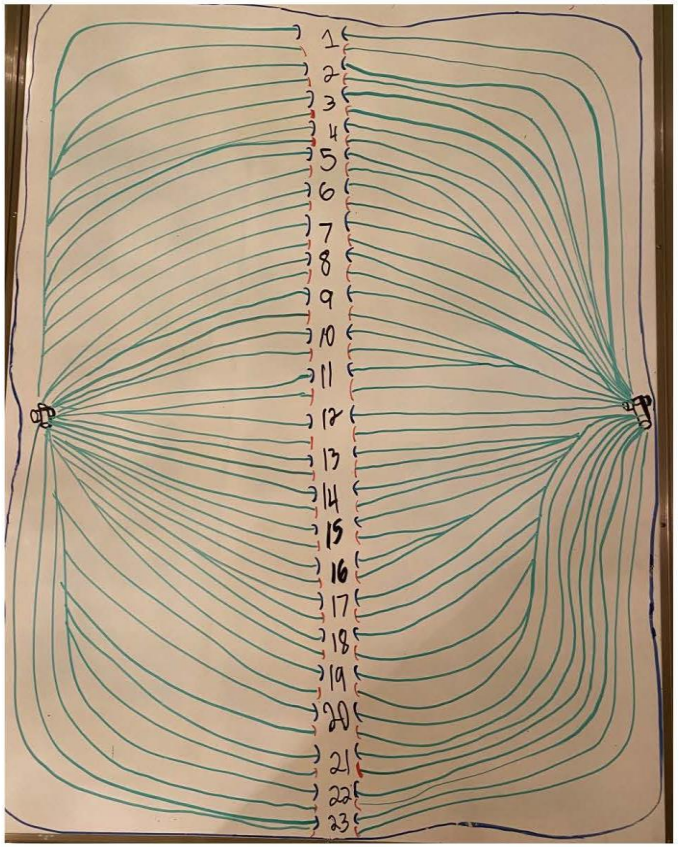
Mitosis(Male) Telophase (*2n*)

- 23 identical pairs of chromosomes are on each side of the cell
- The nuclear envelope reforms
- Two daughter cells start to form



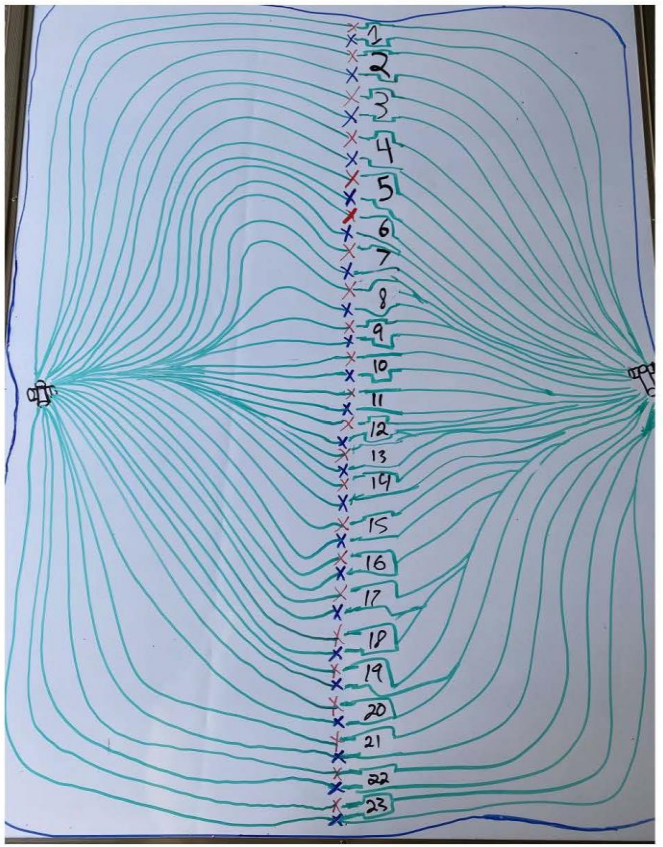
Mitosis(Male) Anaphase (*2n*)

- Sister Chromatids are pulled apart



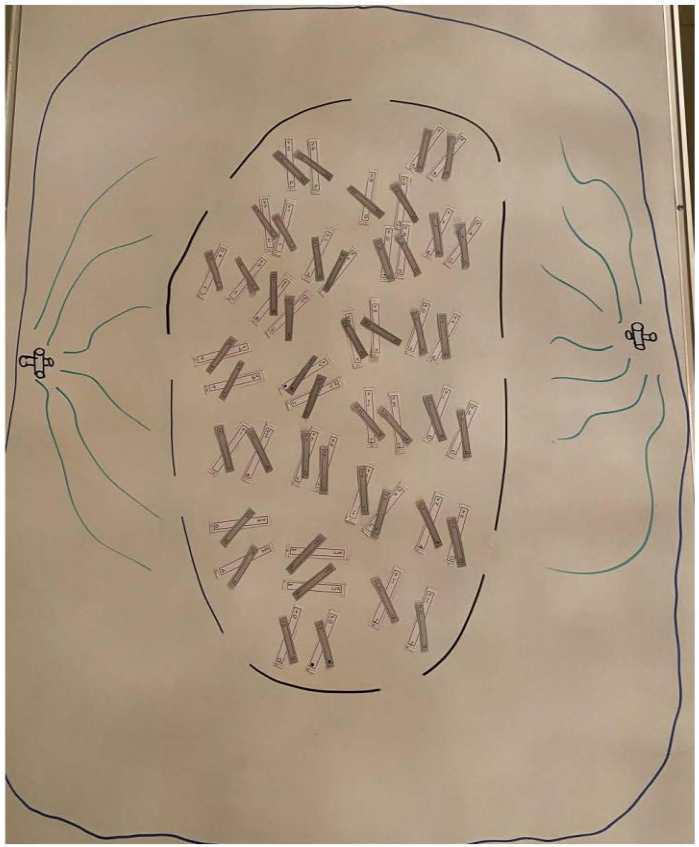
Mitosis(Female) Metaphase *2n*

- Chromosomes line up along equator of cell
- Spindles attach to each chromosome
- Red are maternal and blue are paternal chromosomes



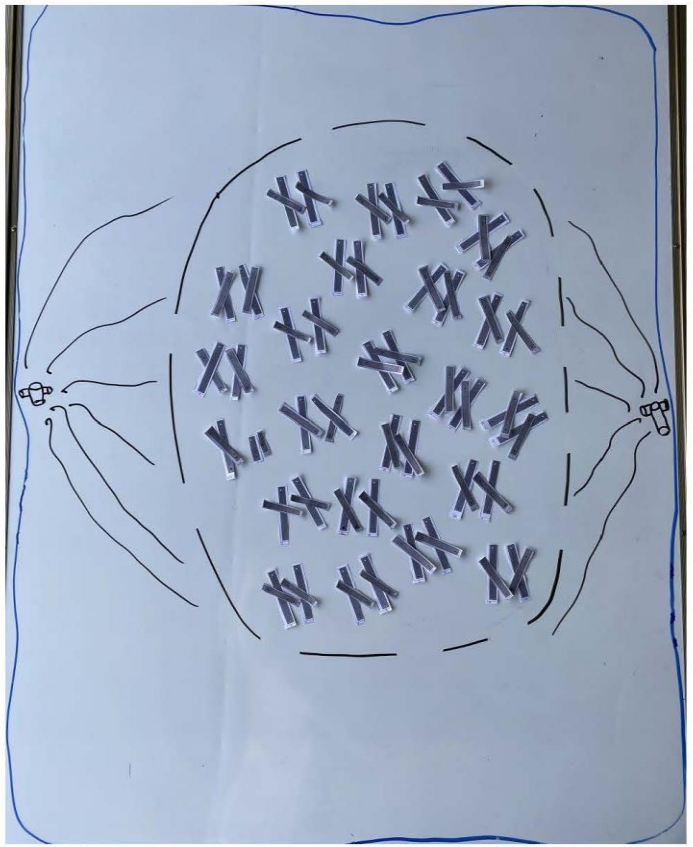
3)
Mitosis(Female)
Prophase *2n*

- Chromatin condenses into chromosomes (sister chromatids)
- The nuclear envelope breaks down
- Centrioles move to poles
- Spindle fibers start to form



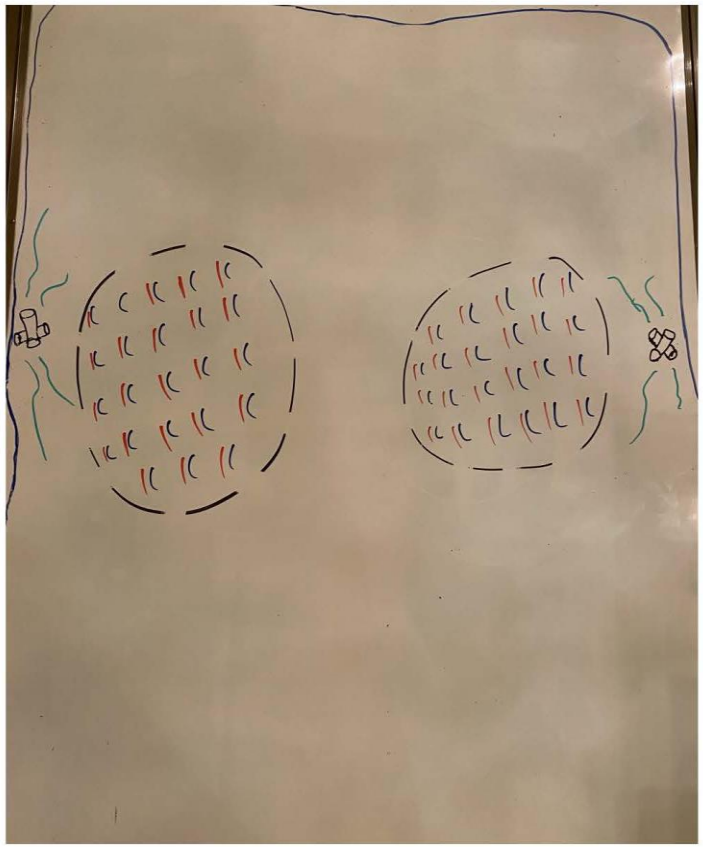
4) Meiosis(Male) Prophase I (2n) before crossing over

- Chromatin condenses into chromosomes (sister chromatids)
- The nuclear envelope breaks down
- Centrioles move to poles
- Spindle fibers start to form



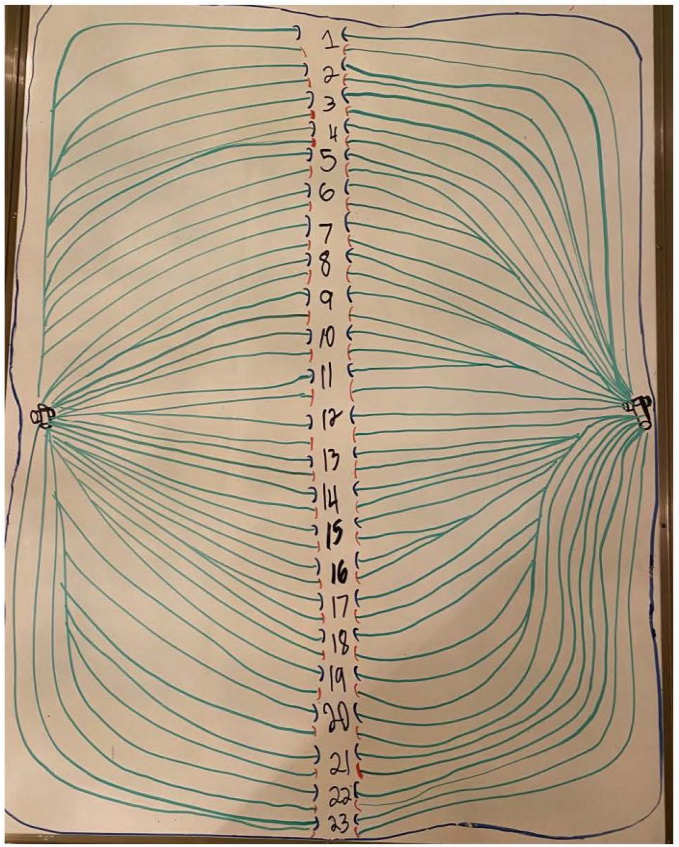
Mitosis(Female) Telophase *2n*

- 23 identical pairs of chromosomes are on each side of the cell
- The nuclear envelope reforms
- Two daughter cells start to form



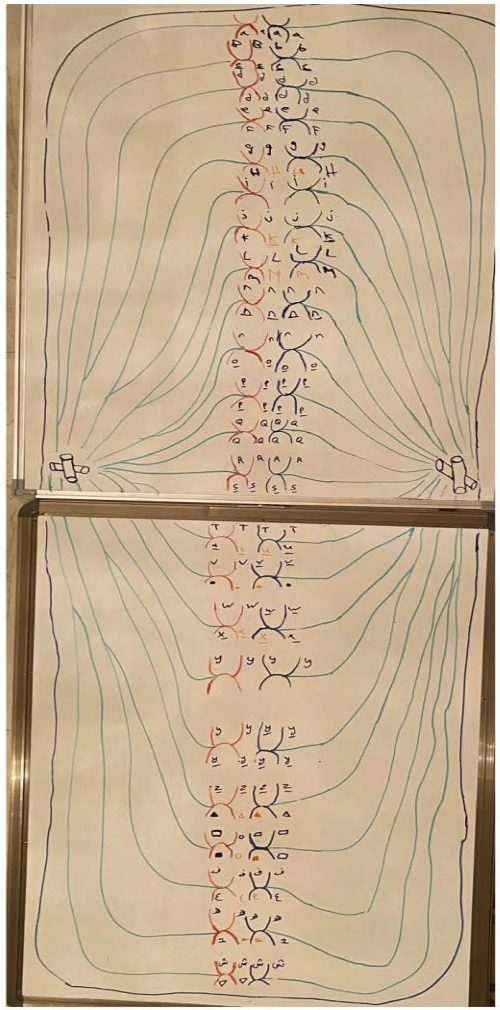
Mitosis(Female) Anaphase *2n*

- Sister Chromatids are pulled apart



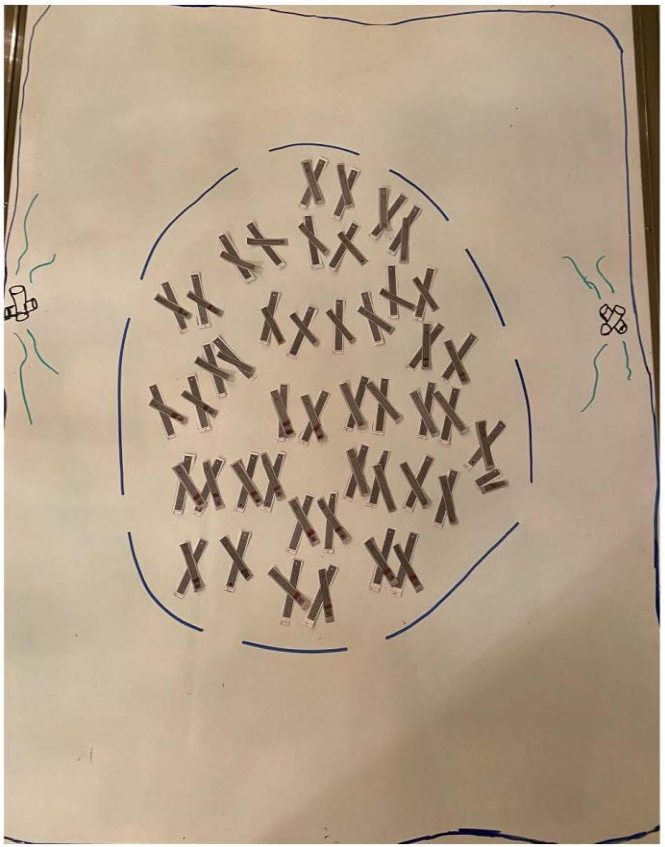
Metaphase I 2n

- Spindle fibres attach to centromeres
- Chromosomes align in the center of the cell



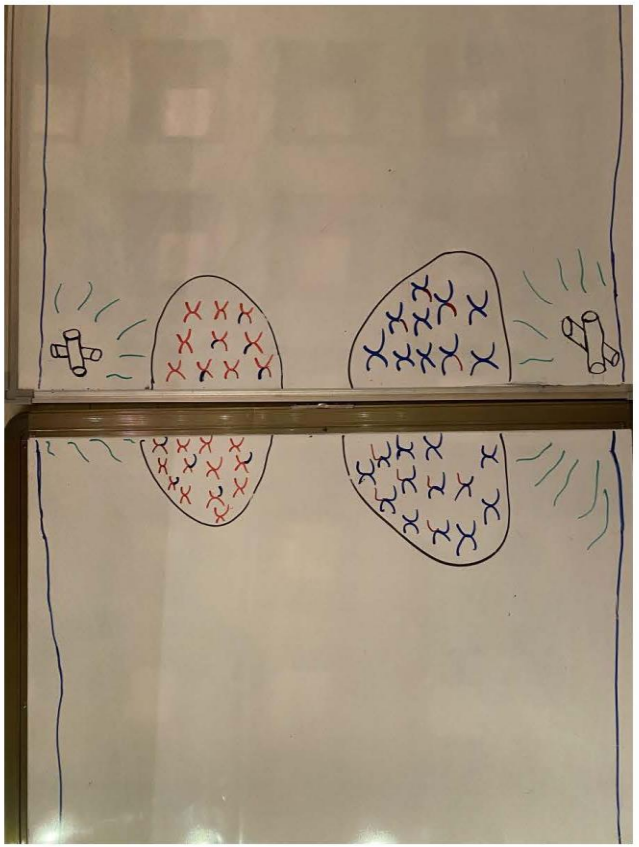
Prophase I (2n) after crossing over

The chromosomes that undergo crossing over are chromosomes number 6,8,9,14,15,16,19,20,21,21



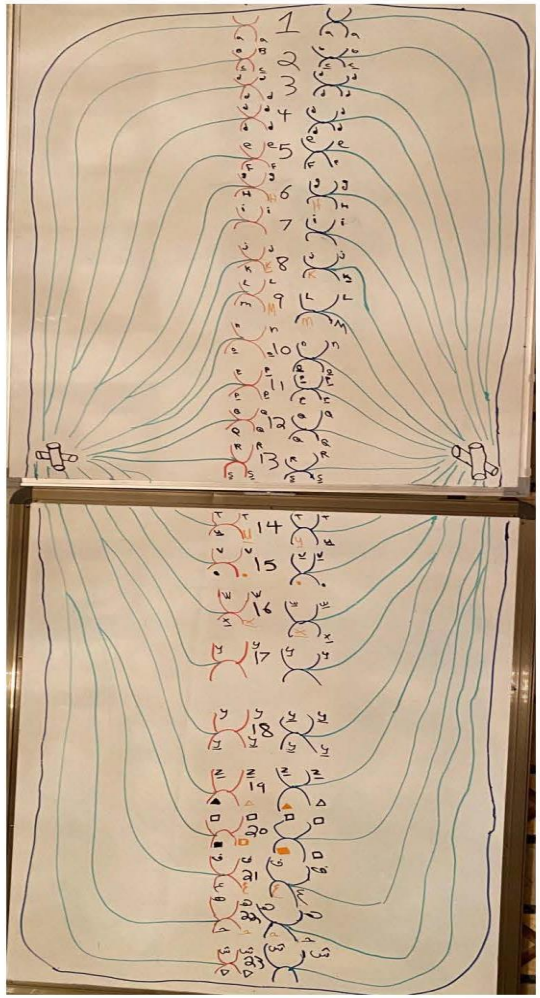
Telophase I (n)

- At each pole there is a complete haploid set of chromosomes
- Each chromosome has two sister chromatids
- Spindle fibers disappear



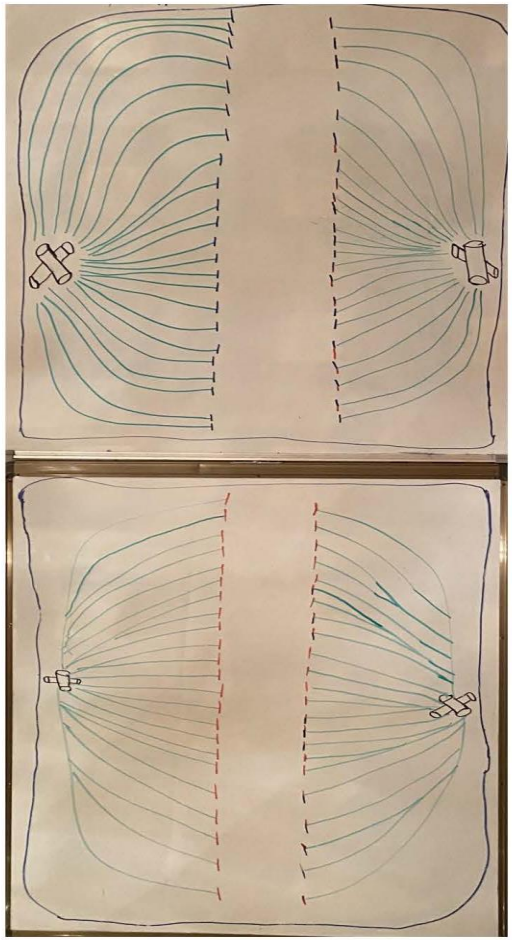
Anaphase I (n)

- Chromosomes separate and start to move to opposite poles
- The sister chromatins remain attached to each other



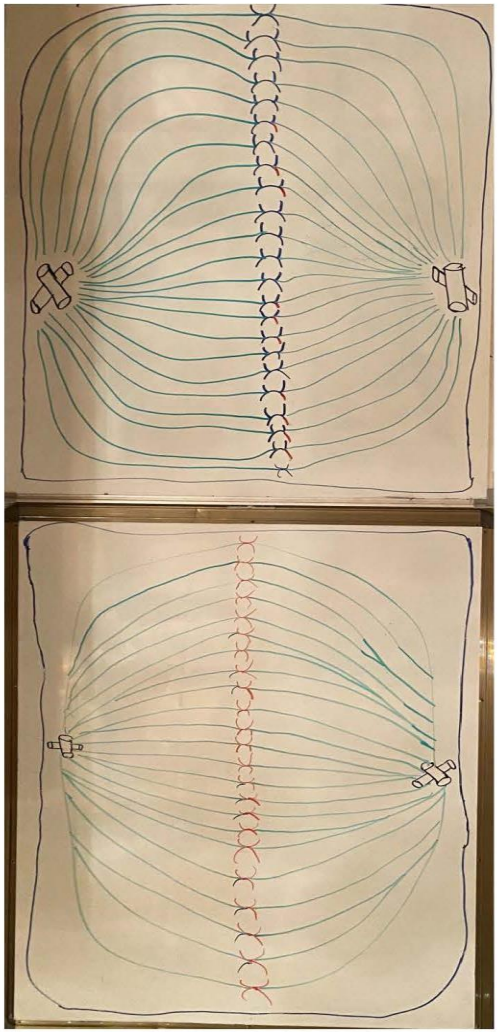
Anaphase II (n)

- Sister chromatids separate and move to opposite poles



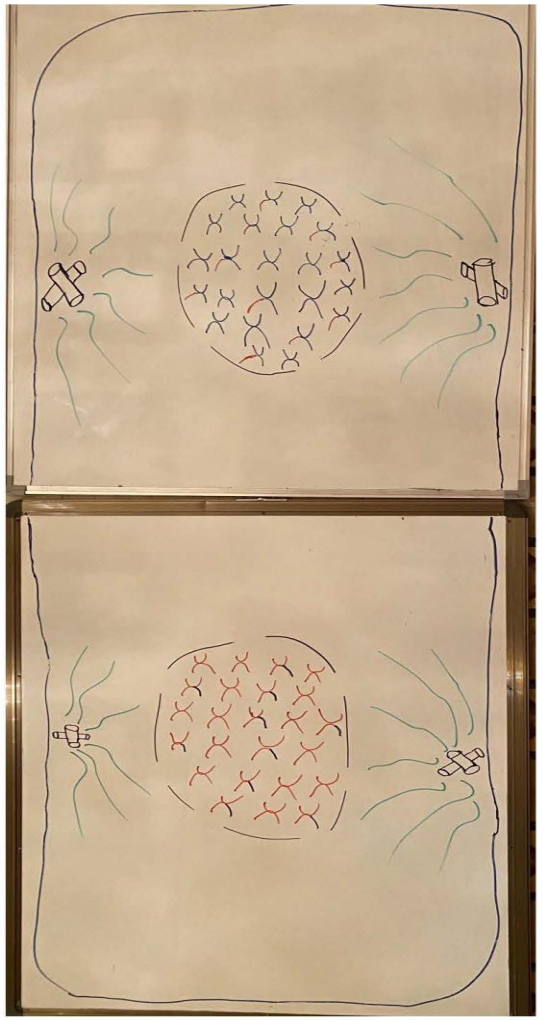
Metaphase II (n)

- Chromosomes line up individually in the equator of the cells
- Spindle fibers attach to the centromeres



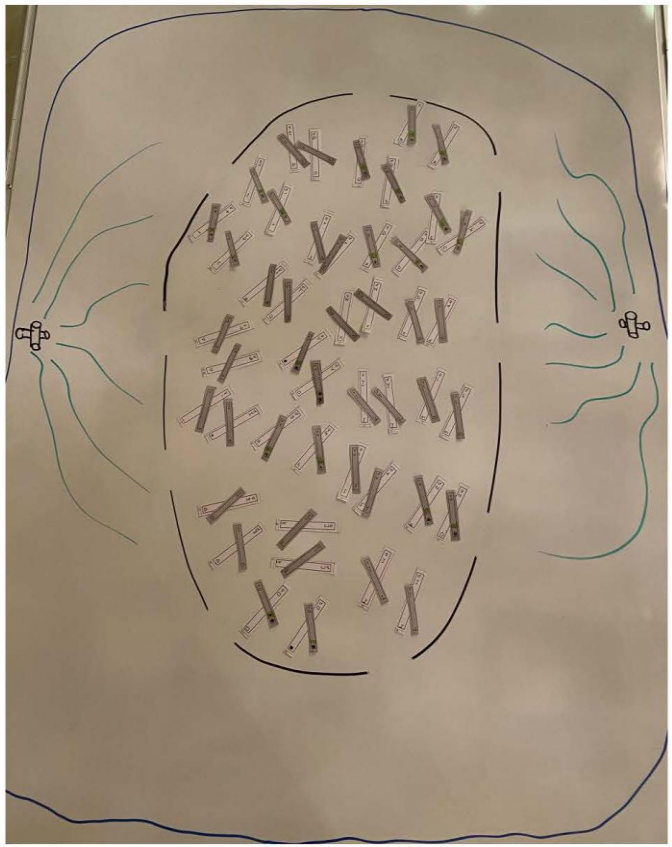
Prophase II (n)

- Spindle fibers form
- Nuclear envelope breaks down
- (sister chromatids)



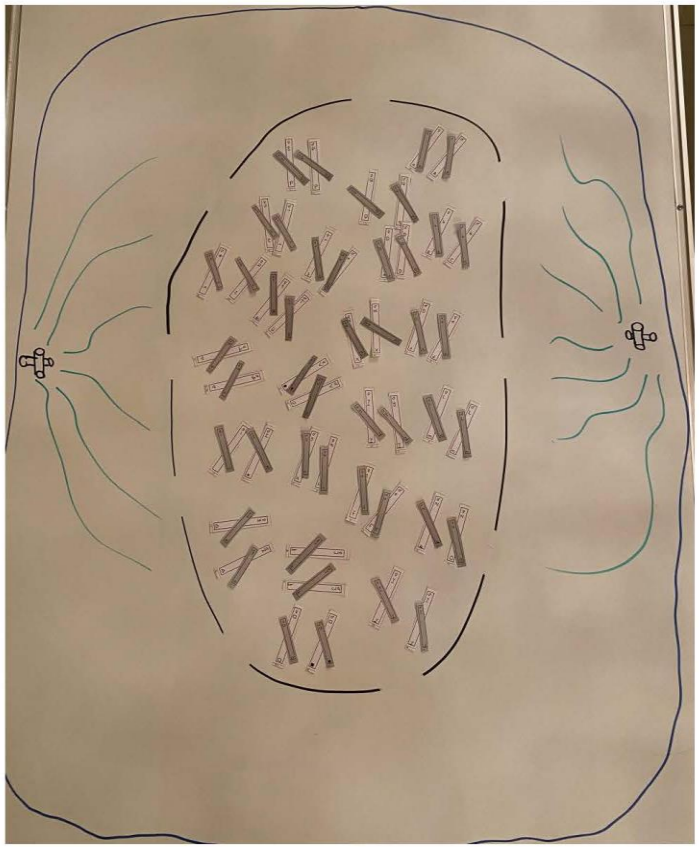
Prophase I (2n) after crossing over

The chromosomes that undergo crossing over are chromosomes number 1,2,3,6,10,12,15,20,21,22.



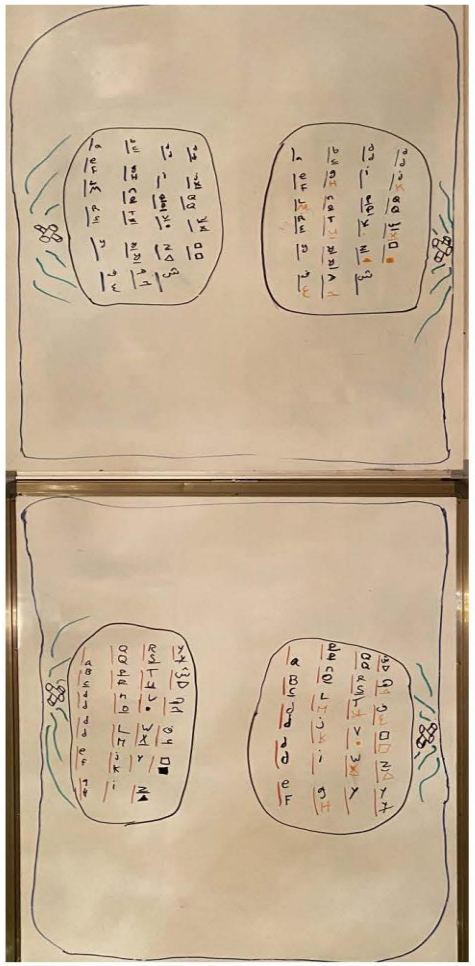
5) Meiosis(Female) Prophase I (2n) before crossing over

- Chromatin condenses into chromosomes (sister chromatids)
- The nuclear envelope breaks down
- Centrioles move to poles
- Spindle fibers start to form



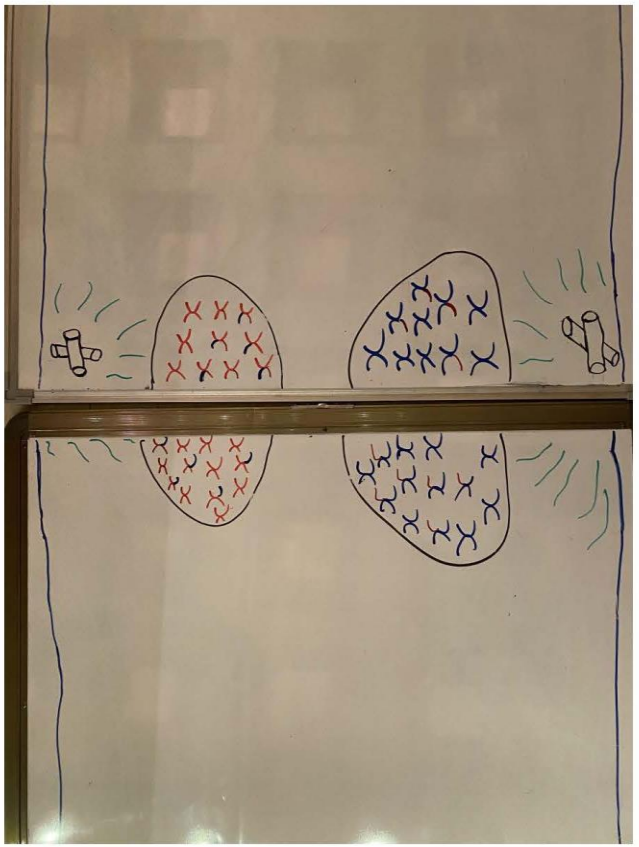
Telophase II (n)

- Nuclear envelope forms
- Four different haploid daughter cells will form
- Spindle fibers disappear



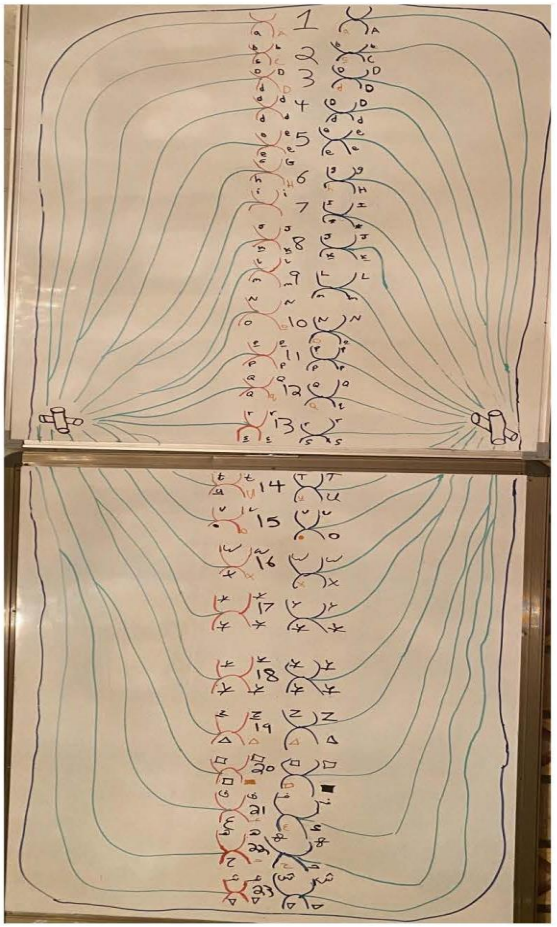
Telophase I (n)

- At each pole there is a complete haploid set of chromosomes
- Each chromosome has two sister chromatids
- Spindle fibers disappear



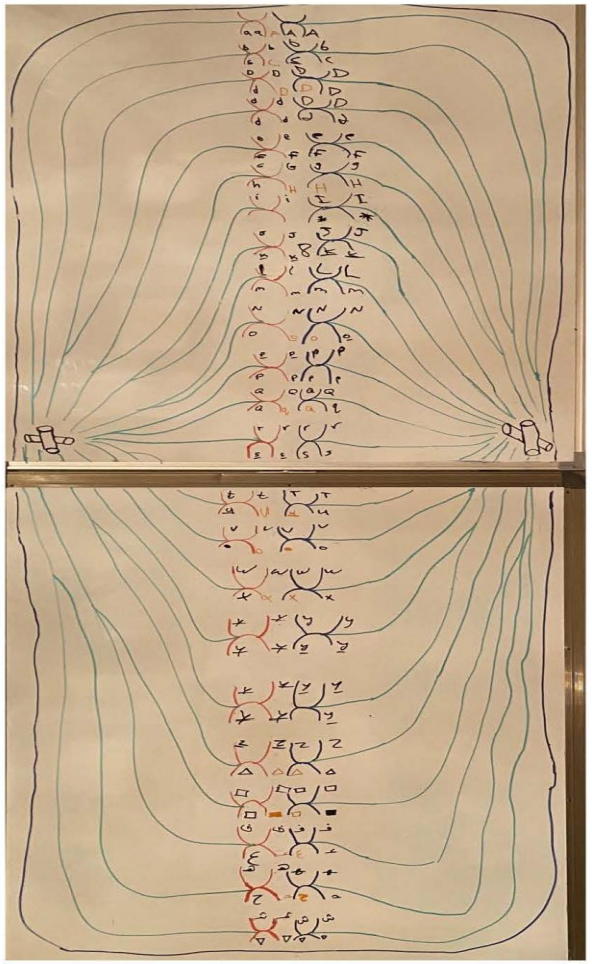
Anaphase I (n)

- Chromosomes separate and start to move to opposite poles
- The sister chromatins remain attached to each other



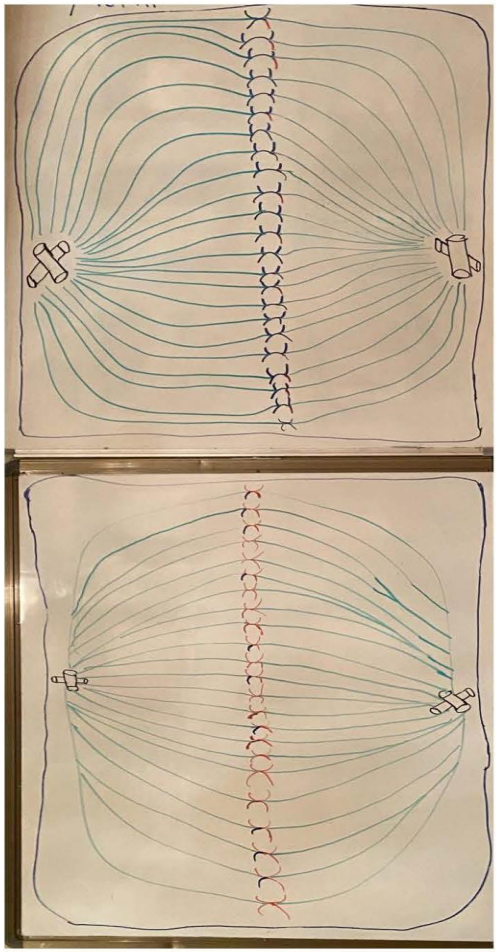
Metaphase I 2n

- Spindle fibres attach to centromeres
- Chromosomes align in the center of the cell



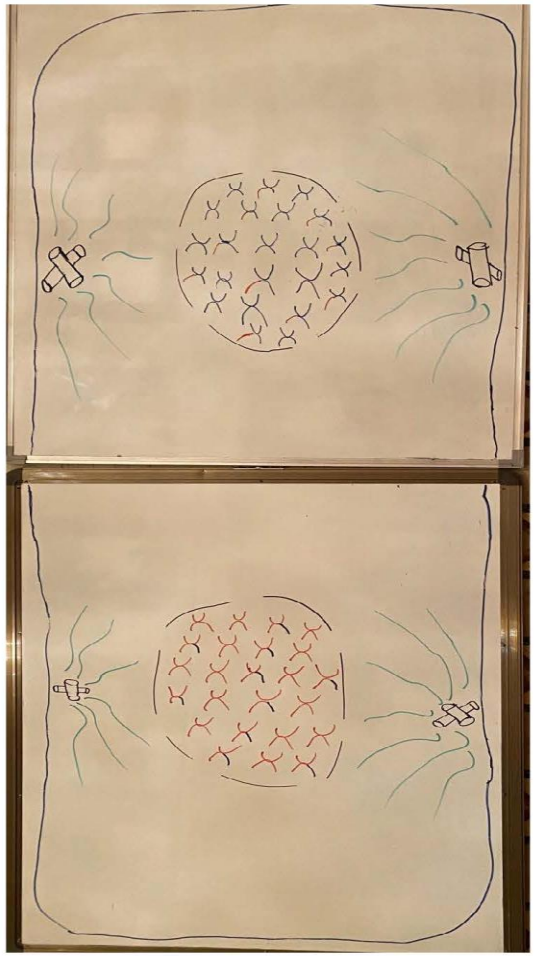
Metaphase II (n)

- Chromosomes line up individually in the equator of the cells
- Spindle fibers attach to the centromeres

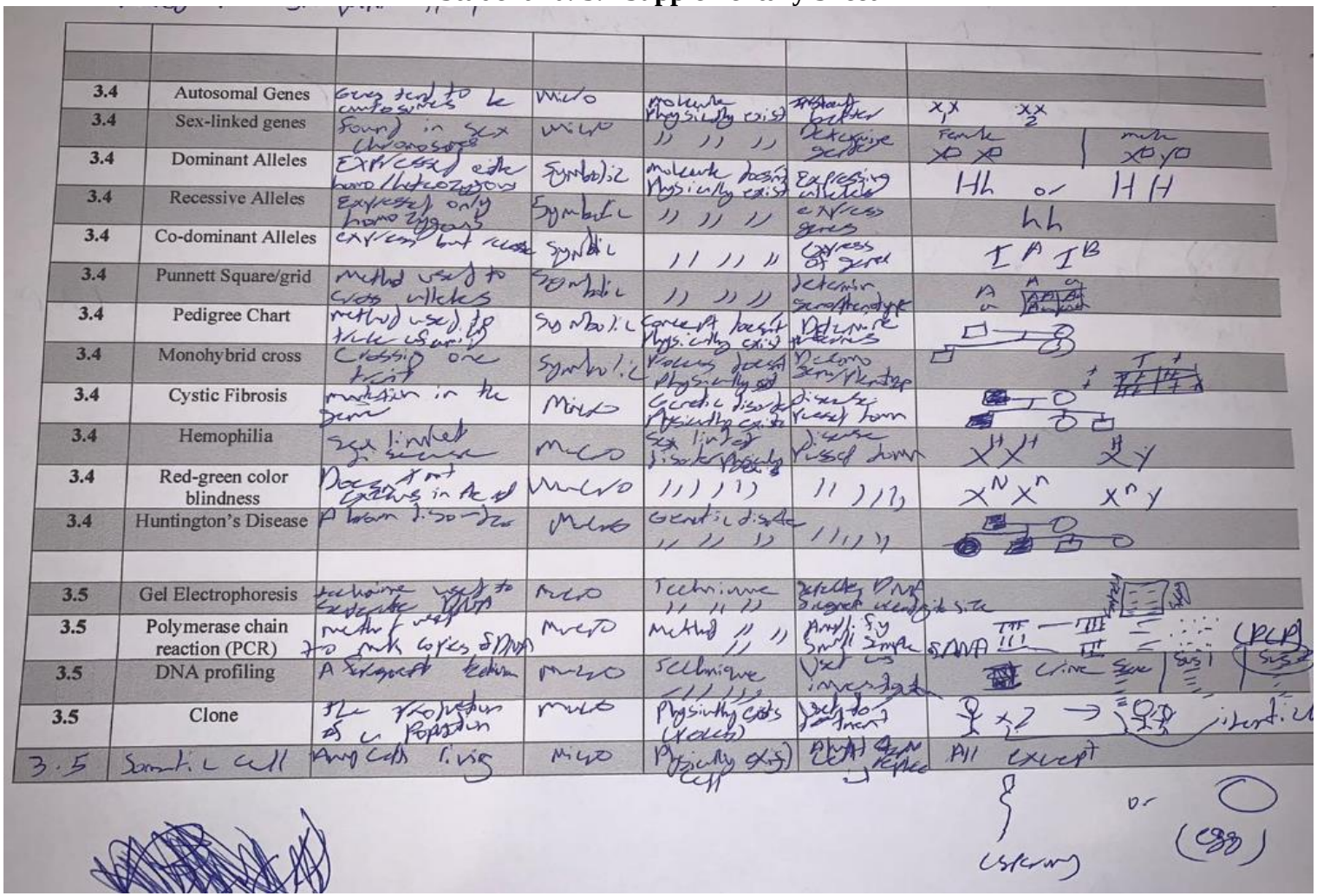


Prophase II (n)

- Spindle fibers form
- Nuclear envelope breaks down
- (sister chromatids)

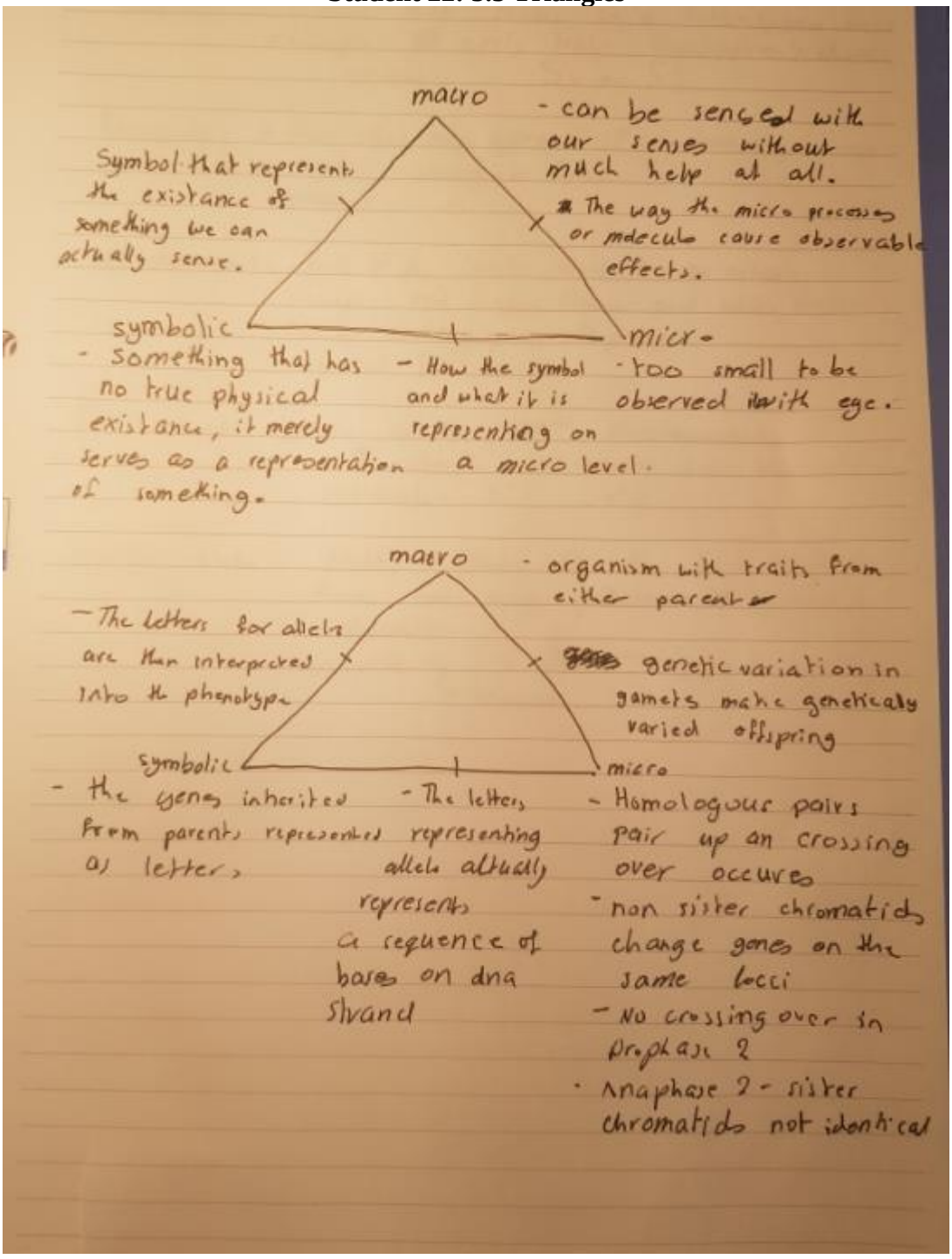


Appendix 15B: Student Supplementary Unit Sheet Samples
Student 10: 3.4 Supplementary Sheet



3.4	Autosomal Genes					
3.4	Sex-linked genes					
3.4	Dominant Alleles					
3.4	Recessive Alleles					
3.4	Co-dominant Alleles					
3.4	Punnett Square/grid					
3.4	Pedigree Chart					
3.4	Monohybrid cross					
3.4	Cystic Fibrosis					
3.4	Hemophilia					
3.4	Red-green color blindness					
3.4	Huntington's Disease					
3.5	Gel Electrophoresis					
3.5	Polymerase chain reaction (PCR)					
3.5	DNA profiling					
3.5	Clone					
3.5	Somatic cell					

Appendix 15C: Student Triangle Samples
Student 22: 3.5 Triangles



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