# Unpacking procedural and conceptual difficulties of grade 13 students in solving problems in genetics crosses

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**Abstract** This study examines the procedural and conceptual difficulties experienced by biology students when solving genetics cross problems related to inheritance. A qualitative case study was used and data were gathered from grade 13 (age 18) biology students in Mauritius. Initially, students who engaged in four problem-solving exercises were observed and their work was collected and analysed to elucidate their procedural difficulties. Then, individual semi-structured interviews were undertaken with the students. The results show that most students found it difficult to connect the various levels at which genetics can be understood (molecular, microscopic, macroscopic and symbolic). This severely hampered their understanding of genetics and their ability to answer correctly questions to do with genetics crosses. Suggestions are made as to how this might be remedied.

Understanding genetics crosses is a well-established problem (Dougherty *et al.*, 2011). Although familiarisation with genetic information may allow students to solve genetics crosses, being able to solve such crosses can nevertheless go hand in hand with an incomplete knowledge of inheritance because the genetics diagrams employed in solving genetics crosses do not on their own show the patterns in gene transmission.

For a good understanding, students must move to the abstract level of genetics. Unfortunately, the complexity inherent in understanding genetics can lead to students rote learning or unthinkingly applying rules they have learnt. To solve problems in genetics, students need to understand the relevant theory, which necessitates a degree of comprehension that is organised into interrelated levels associated with various subject disciplines, including biology, biochemistry and mathematics.

There are four interrelated levels of knowledge involved in learning genetics (Figure 1), namely molecular (biochemical), microscopic (cellular), macroscopic (organisational) and symbolic (representational) (Chu and Reid, 2012). Some students may cope well with a particular level but experience major concerns with another. This study explores the extent to which students are acquainted with the various levels and their challenges.

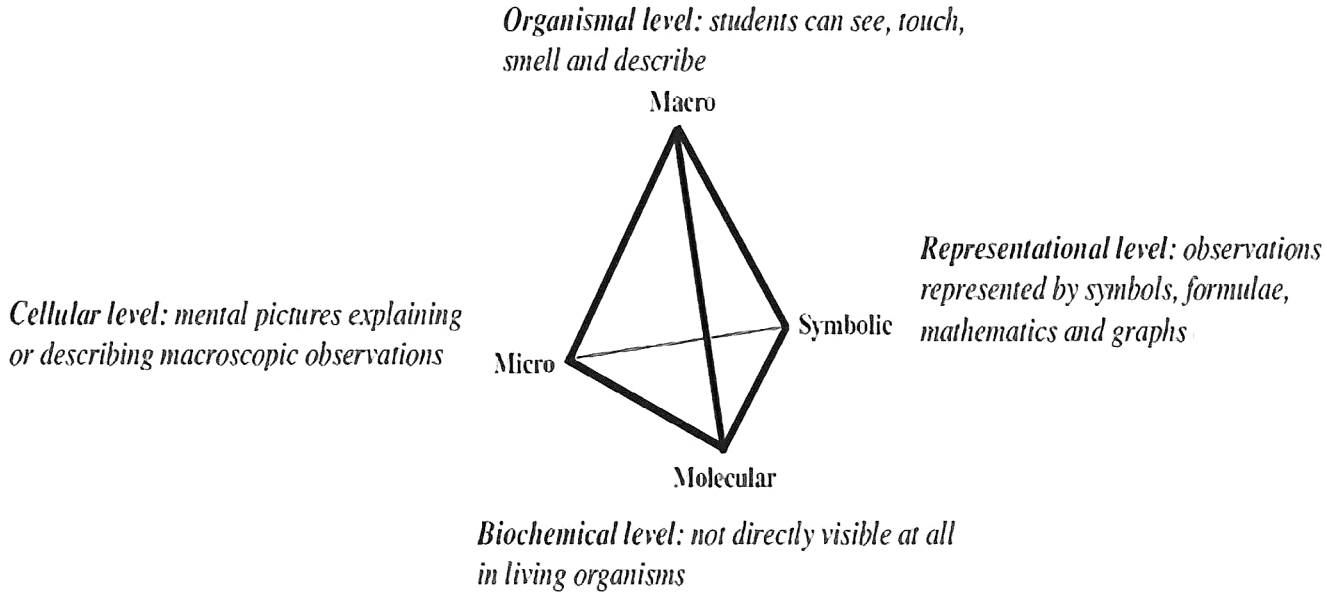


**Figure 1** The four levels at which genetics can be learnt (Chu and Reid, 2012: 287)

## Methodology

A descriptive case study was adopted to investigate the difficulties experienced by grade 13 (A-level, age 18) biology students in Mauritius when attempting to solve genetics problems. A private, secondary, non-fee-paying school was selected, partly on the grounds of ease of access. The students were in the science stream, and so also learning chemistry and mathematics, and consisted of boys and girls. These students had been studying biology from their early years of secondary schooling and had passed their grade 11 national examinations (Cambridge O-level). They had been taught about simple monohybrid inheritance and the relationship of meiosis to gamete formation. Purposive sampling was used, consisting of eight grade 13 biology students who volunteered for the study. A mix of low-, medium- and high-performing students, based on their results on past tests and written examinations, were selected as participants. Two sources of qualitative evidence (problem-solving exercises and interviews) were used. Genetics is a biology topic that is presented quite similarly at upper high school level in many countries, so our findings are likely to be widely applicable.

Data were collected in two stages. During the first stage, the participants had to solve four genetics crosses and show the inheritance patterns of particular traits. Participants' worksheets were collected and their procedural steps, adapted from Cambridge International AS and A-level Biology 9700 syllabus for 2019–2021, were examined. The second stage consisted of semi-structured, one-to-one interviews. An inductive analysis was used because of its flexibility and ability to provide a rich description of the problem phenomena. The study complied with the ethical guidance in BERA (2018).

## Results

### *Procedural difficulties*

The first stage of the study focused on the students' abilities to use the appropriate procedural steps while attempting to solve four genetics crosses. One major procedural difficulty is the construction of an appropriate symbolic key, which constitutes the first step of the problem-solving exercise. These difficulties are summarised in Table 1.

The first procedural step is for students to identify parental phenotypes and genotypes. Most students encountered difficulties in problem four. This was mainly attributed to the inappropriate use of superscripts (for example, $X^h$ correctly indicates that an X chromosome carries the allele for haemophilia and $X^H$ that an X chromosome carries the normal allele, whereas the Y chromosome does not have the gene in question and so at this locus cannot be represented with superscripts). It was also found that the use of superscripts in X-linked inheritance further confused students when constructing the required symbolic key in codominance. For example, student S8 did not use a superscript to represent the codominance allele because they thought that superscripts are only used in X-linked inheritance. Furthermore, it was found that the construction of a symbolic key for X-linkage, representation of a carrier female and X-linkage disease among males were seen to be the most challenging tasks. For example, the response of S3 indicated that the difficulties in using the required symbolic key during X-linkage disease are due to confusion about which X chromosome carries the dominant allele. Hence, S3 incorrectly represented a carrier mother as having two dominant alleles and incorrectly indicated that a Y chromosome had a recessive allele.

The second procedural step was the representation of genetics concepts and processes. Many problems encountered in this step originated from the mistakes that students had committed during the first step. For example, a mistake in determining the parental genotypes correlated with an incorrect symbolic key to alleles. Mistakes were more evident for dihybrid and X-linkage problems. Furthermore, even though some students had been able to generate the correct parental genotypes, they produced incorrect gamete combinations. It was found

**Table 1 Student difficulties with symbolic representation**

| Problem | Difficulties | Student code |
|---|---|---|
| One | Inappropriate use of the symbol to represent the recessive allele. | S6 |
| Two | $C^{RW}$ is an incorrect symbolic key for roan (codominance). | S2 |
| | Allele should be represented as superscript instead of capital 'R' (student uses RR instead of $C^RC^R$). | S8 |
| Three | Inability to construct a symbolic key for dihybrid inheritance. | S2, S7 |
| Four | Some students represented X-linkage inheritance as a simple autosomal inheritance. They did not use the symbol 'X'. | S3, S5 |

that several of the students simply rote-learnt the procedural steps and 'solved' the genetics problem in a non-meaningful fashion. These students seemed to have a poor understanding of allele segregation and independent assortment, something that was confirmed during the interviews with them. Most of the students were able to apply the first three procedural steps during simple monohybrid and codominance crosses, but, in dihybrid crosses, although approximately half the students correctly identified the parental genotypes and phenotypes, few correctly represented the gametes. In X-linked inheritance, few students correctly identified the parental genotypes and phenotypes. However, many students were able to proceed to the next (third) step to represent gamete formation and the genetics cross. This indicated a form of rote learning of the procedural steps. The representation of gametes in a dihybrid cross and portraying the parental genotype using appropriate alleles in X-linkage inheritance were the most problematic tasks. These difficulties are highlighted in Table 2.

The final (fourth) procedural step was to show the offspring genotypes and phenotypes. Problems one(b), two and four(a) required the students to perform simple inheritance forward problem-solving. Seven of the students correctly identified the offspring genotype and phenotype for problem one, six did so for problem two, four did so for problem four, but none for problem three. Regarding the offspring, seven students correctly showed the genotypic ratio for problem one but none for any of the other three problems; furthermore, concerning the phenotypic ratio, five students were correct for problem one, two for problem two, and none for problems three or four. It seemed that when students reached the end of the problem-solving exercises, they tended to omit the offspring genotypic and phenotypic ratios.

**Table 3** Number of students successfully reaching an answer in the last procedural step

| Problem | Correct identification of: | |
|---|---|---|
| | Offspring genotype and phenotype | Offspring genotypic ratio |
| **One** | 7 | 7 |
| **Two** | 6 | 0 |
| **Three** | 0 | 0 |
| **Four** | 4 | 0 |

Problem one(c) and four(b) required backward problem-solving. Most students correctly stated the genotype of the parents for problem one(c) (an autosomal monohybrid cross). However, for problem four(b) (X-linked inheritance), only one student correctly solved and explained the result, despite all the students having been taught previously about X-linked inheritance. The other students either provided a genetics diagram without any explanation (suggesting rote learning) or provided only a partial explanation. S2 correctly drew the

**Table 2** Difficulties in representing genetics concepts and processes

| Problem | Difficulties | Student code |
|---|---|---|
| One | Terminology misunderstood:<br>• One parent is heterozygous for black eyes, thus cannot be represented as 'BB'.<br>• Confusion between genotype and phenotype. | <br>S6<br>S1 |
| | Shows only one gamete produced from a parent instead of two. | S1 |
| | Genetics cross not drawn to demonstrate fertilisation. | S1 |
| Two | Genotype for roan colour coat wrongly represented. However, most procedural steps were represented [students had previously been taught what 'roan' means]. | S2, S8 |
| Three | Wrong allele combination during gamete formation. However, correct parental genotypes were shown and Punnett square appropriately used. | S5 |
| | Terminology misunderstood – heterozygote animal for grey fur and long tail cannot be represented as 'GgTT'. Both traits should be in the heterozygous condition (GgTt). | S2 |
| | Shows only one gamete for pure-bred parent instead of four. | S1, S2 |
| | Failed to construct a Punnett square, although parental genotype and gamete formation correctly identified. | S7 |
| | Represented parental genotype as gametes and gametes as F1 generation. However, Punnett square correctly used. | S8 |
| Four | Since the disease is X-linked, the Y chromosome in a male cannot carry or be represented with an allele. | S3 |

genetics diagram for problem four(b) but failed to state the maternal genotype, as specified in the question. It seems likely that S2 had simply rote-learnt the steps for providing a genetics diagram without having a meaningful understanding of the process behind it.

S5 considered the mother to be 'homozygous recessive', which is wrong because, in the case of haemophilia, this combination is (almost always) lethal for females. On the other hand, S7 correctly drew the genetics diagram and the parental genotypes were well identified.

The above findings demonstrate that the majority of the students failed to use all the required procedural steps when attempting to solve the genetics problems. Most students managed to solve the monohybrid and codominance crosses, which was unsurprising as both involved only simple autosomal inheritance. Some students correctly solved the genetics crosses but lacked certain procedural steps. However, no students were able to solve the dihybrid cross correctly using all procedural steps, despite having been introduced previously to dihybrid crosses; typically, they failed to show the correct possibilities for the gamete combinations. Regarding the X-linkage problem, students were more likely to be unsuccessful than successful.

### *Conceptual difficulties*

The second stage of our research builds on the first and seeks to understand students' conceptual difficulties about their genetics reasoning through semi-structured interviews. The interviews enabled additional questions to be posed, based on the student problem-solving exercises and responses. The key findings from the interviews are summarised in Table 4.

One major conceptual challenge was that some students only partially understood key genetics concepts, as highlighted in Table 5. Although the majority of students understood the process of meiosis and that it results in gamete formation, four of the students were unable to identify on their genetics diagrams where meiosis took place. Two of the students correctly referred to gametes as sex cells and identified them as haploid, but six associated the formation of gametes with the fusion of two alleles. On further probing during the interview, it seemed that students confused gamete formation with fertilisation. Six of the students correctly described the process of fertilisation. However, when asked what the cross lines drawn on their genetics diagrams (which result in the F1 generation) represented, only two of the students correctly referred to fertilisation. Two referred to meiosis and the other four only to the fusion of gametes. This demonstrates that most students had a poor understanding of these key genetics concepts and this impacted on their ability to relate these concepts to their solution process. A related difficulty was students' variable understanding of genetics terminology.

Overall, the findings indicate that the inability of most of the students to use the correct procedural steps is probably the result of rote learning and a lack of conceptual understanding of key genetics concepts, and their inability to relate these concepts to their problem-solving exercises.

## Discussion

For a better comprehension of genetic phenomena, students must be able to understand the interconnections among four levels, namely the microscopic, symbolic, macroscopic and molecular levels (Chu and Reid, 2012). Similarly, Mussard and Reiss (2022) highlighted that learners of genetics need to reason between these levels. Figure 2 provides an example of a student's successful response to question 1a: '*Choose suitable symbols for these alleles, and then draw a monohybrid genetic diagram to show the probable results of a cross between a heterozygous parent and a homozygous recessive parent. Clearly write the proper labelling at each step*'. On Figure 2 we have added, in boxes, information about the four

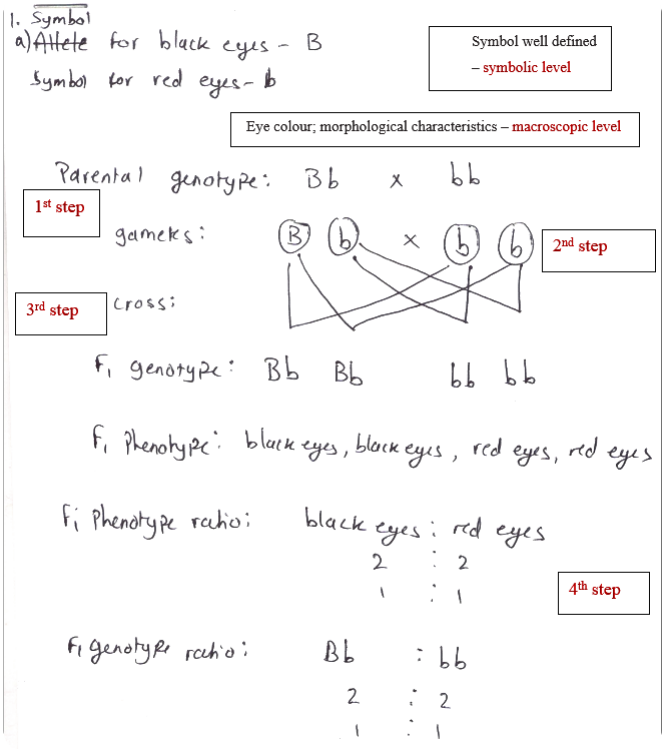


**Figure 2** An example of a student's answer to a genetics problem that successfully uses the four procedural steps identified and makes clear reference to the symbolic and macroscopic levels

**Table 4** Main conceptual difficulties as revealed through interviews

| Conceptual challenges | Difficulties encountered |
|---|---|
| Lack of meaningful solutions | Four students were confused or had a poor understanding of genetic concepts and could not relate these concepts appropriately to their problem-solving solution. For example, many students did not understand what a gamete is and were not able to represent its formation on the genetics diagram.<br>Additionally, students did not understand the concept of 'pure-bred' and were unable to represent this using the appropriate symbol. |
| Poor understanding of key genetics concepts | Confusing gamete formation with fertilisation. |
| | Seemed to have learnt genetics concepts separately from genetics diagrams. |
| Misunderstanding of terminology | Use of gene and allele interchangeably. |
| | Many students associated pure-bred with homozygous dominant traits. |
| | Some students were hesitant when trying to answer certain interview questions or were confused about the use of the appropriate genetics terms. |
| Difficulties in understanding X-linked inheritance | Seemed not to understand that males have only one X chromosome, and so a recessive allele would cause the disease in males. |
| | Treat X-link inheritance as autosomal. |

**Table 5** Students' responses to key genetics concepts

| Genetics concept | Student responses during interview | No. of students |
|---|---|---|
| Allele | Different/alternative form of a gene [good understanding]. | 2 |
| | Associate it with a chromosome – found on a chromosome. | 2 |
| | Relate to the formation of genotype or contain the dominant or non-dominant characteristics. | 2 |
| Gene | Section of DNA coding for a specific character in the body [good understanding]. | 2 |
| | Found on DNA. | 4 |
| | Give specific characters, such as eye colour. | 2 |
| Is a gene a protein? | No [good understanding]. | 2 |
| | Yes. | 4 |
| | No idea. | 2 |
| Composition of gene | Nucleotide [good understanding]. | 2 |
| | Amino acid. | 2 |
| | No idea. | 4 |
| Pure-bred | Only one student understood this term and identified it as 'not in heterozygous condition but in homozygous which can be either dominant or recessive' [good understanding]. | 1 |
| | The majority considered pure-bred as a condition in 'the homozygous dominant' state. | 7 |
| Carrier | Carry/transmit the disease but do not show any sign of illness [good understanding]. | 4 |
| | Carry a faulty gene/allele. | 2 |
| | Carry one recessive allele for the disease. | 2 |
| Genotype and phenotype | Identified genotype as the allele the individual possesses and phenotype as the physical appearance of the individual [good understanding]. | 8 |

procedural steps and the symbolic and macroscopic levels.

When attempting to solve a genetics cross, the first procedural step requires the construction of a symbolic key. Confusions in symbolic representation can arise because of the different symbol systems. Each symbol system follows its code; thus, students are compelled to learn how to translate these symbols before attempting the problem-solving exercises, which may lead to mental overload. Cognitive conflict can arise in students when there is a shift from one representation system to another. For example, students may correctly use a symbolic key for monohybrid inheritance but have difficulties with dihybrid crosses and X-linked inheritance which require different symbolic representation.

A poor understanding of the relationship between sexual reproduction and the mechanisms of genetic inheritance may hinder students' ability to relate biological phenomena to what they have learnt in genetics. However, once a student can use relevant prior knowledge and apply it to what they are learning from their genetics curriculum, their mental framework will trigger a succession of changes that will modify existing concepts and provide links with older ones. When rote learning takes place, students may assimilate a new concept and add it to their cognitive structure without the new concept interacting with existing knowledge. Learning concepts as isolated entities may result in a dearth of logical meaningfulness in a student's cognitive structures and shortcomings in their understanding of genetics (Cavallo, 1996). When students can solve simple inheritance problems with reasonable competence but have difficulties with dihybrid and X-linked inheritance, this shows that they may possess domain-specific knowledge but lack domain-general knowledge. Students would be likely to benefit, before tackling these harder problems on their own, by being explicitly instructed through the use of worked examples.

The symbolic level can often bridge the macroscopic and microscopic levels. Whereas the microscopic and symbolic levels can be fairly readily addressed during teaching, the macroscopic level can perhaps best be taught by the representation of phenotypes through breeding experiments (e.g. of *Drosophila*), which are not usually undertaken in Mauritian schools. Because of limited resources and time constrains, the macroscopic level is, perhaps surprisingly, the least considered of the four genetics levels at the Mauritian secondary school level. Consequently, in future curriculum planning, new teaching strategies, such as practical work with ears of corn and the use of animations or simulations, could be used to portray experimentation at the macroscopic level, helping students to relate what happens at other levels to what happens at the macroscopic level.

Problem-solving in genetics and inheritance should be well organised in a stepwise manner. These procedural steps include: representing the alleles using symbolic keys; defining parental phenotypes and genotypes; showing how alleles segregate to form gametes; making the cross to show how the alleles assort independently to form new combinations among offspring; and determining the genotypic and phenotypic ratio of the offspring (F1 generation).

As found in some other studies, students were confused about different levels of organisation and tended to explain a particular biological phenomenon at only one level, failing to interrelate concepts on different levels, which Verhoeff (2003) characterised as a lack of vertical coherence. A vertical alignment of the biology curriculum should enable the gradual development of students' knowledge, building on preceding learning encounters, and this may foster a positive learning experience in genetics. Students' misconceptions at a particular level can affect their understanding at other levels. For example, some students cannot explain how an allele for colour-blindness (in X-linked inheritance) can be passed from a mother to one of her children, with the result that a son may be colour-blind, even though the trait appears in neither parent. These difficulties arise because traits manifest at the macroscopic level, whereas genes are at the microscopic level, and genotypes at the symbolic level. It seems likely that students would benefit from their teachers making such links explicit.

Students in this study often associated genes with amino acids instead of with nucleic acids. The interviews revealed that this misconception could be attributed to the fact that for these students a gene contains a code to synthesise a protein, and a protein is made of amino acids. Moreover, most molecular structures in living things are not directly visible. Consequently, most molecules must be imagined by students. Genetics is a challenging topic, in part due to its microscopic entities. Visualisation using genetics diagrams can help to make the microscopic world 'tangible'. However, many students solved genetics cross problems with little scientific knowledge of cell division. They were unable to relate chromosome segregation to the independent assortment of alleles, and did not appreciate how meiosis leads to gamete formation. This shows that students are often not able to refer to the requisite biological knowledge to solve problems in new situations. This could also help explain why many students could not think critically and draw from prior knowledge to solve genetics problems.

## Conclusions

The complexity of inherited changes has to do with a comprehension of genetics that necessitates 'to-and-fro' thinking between the four levels of organisation, namely the microscopic, symbolic, macroscopic and molecular (Chu, 2008). However, each level has its degree of complexity (Chu, 2008), with the symbolic level being a representation, using letters or other symbols. It is known that confusion may arise in students' minds from using several symbol systems simultaneously (Gilbert, 2005). As revealed by this study, if students are not familiar with these symbolic representations, they may encounter challenges in visualising what is happening at the microscopic level and in explaining their problem-solving procedures. As a result, students not infrequently have difficulty connecting conceptual knowledge at the microscopic level to phenotypes (at the macroscopic level).

This case study demonstrates that many students tend to rote-learn the procedural steps and may reach a correct solution to a genetics problem but are unable to apply the appropriate genetics concepts, especially with respect to sex-linked inheritance. This may be due to the fact that the Mauritian educational system is mainly examination-centred, catering mostly for students' achievement in terms of grades, rather than identifying whether learning with understanding is occurring. Furthermore, the actual biology curriculum at A-level does not require students to navigate across the four levels of organisation and develop their understanding of the terminology and concepts involved in genetics. We would argue that such navigation should be specified in the curriculum to help students obtain a better understanding of genetics.

Finally, it was noteworthy that in the problems used in this study, little reference was made to the molecular level. With so much of genetics nowadays requiring an understanding of molecular biology, this finding is significant; a lack of conceptual understanding by students at this level adversely impacts their ability to develop a sound understanding of genetics.

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