Understanding The Genetic Basis Of Cells: The Written Probes

Young People's Understanding
Of, And Attitudes To, 'The New
Genetics'
Working Paper 4

Contents

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Abstract
In this paper, we report findings from a survey of almost 500 students aged 14 - 16. Their knowledge and understanding of the genetic basis of cells was elicited through written questions requiring individual written responses. Findings showed a poor understanding of the processes by which genetic information is transferred - either from cell to cell within an organism or from parents to offspring as a result of sexual reproduction. Few consistent or coherent alternative conceptions could be identified but uncertainty and confusion were widespread. Understanding of the basic structures involved (gene, chromosome and cell) and their relationship to each other, was poor. A summary of the detailed findings is presented and implications for the teaching of genetics, inheritance and gene technology are discussed.

1 Introduction

The work reported in this paper is part of a larger research project on '*Young Peoples' Understanding of, and Attitudes to, The New Genetics*'. The overall aim of this project was to produce baseline data on the understanding of genetics, awareness of DNA technology and attitudes towards DNA technology which young people have at the end of their compulsory science education.

DNA technology is developing at a rapid pace. DNA data bases have been set up, DNA fingerprinting is a routine forensic tool, screening for genetic disease is becoming commonplace and genetically modified food is now on sale. Each of these uses of DNA technology raise important social and ethical issues, for the individual as well as for society. We were interested in the extent to which the National Curriculum prepares young people in England and Wales for the dilemmas and decisions which they will be faced with as a result of these developments. Our focus was therefore on the students' understanding of general principles - that all living things contain genetic information, for example - rather than the detailed recall of content which might be required for exams. We were also interested in the extent to which students could come to a reasoned opinion about specific uses of DNA technology (through identification, discussion and evaluation of relevant issues), and in the scientific knowledge which they might need to draw on in order to do this.

More than 700 young people aged 14 - 16 took part in the whole study, which was based on four main research questions :-

1. What knowledge and understanding of genetics do young people have at the end of their compulsory science education?
2. What knowledge and understanding of new gene technologies do these same young people have?
3. What issues do they perceive as being raised by the application of new gene technologies in particular contexts?
4. What opinions and attitudes do these young people form concerning the application of these technologies?

Research questions 1 and 2 relate to students' knowledge and understanding of genetics and gene technology. This was investigated through a written survey of almost 500 young people and through a series of audio taped group discussion tasks involving 36 young people. Findings from this section of the research are reported in three papers. This paper (Working Paper 4) reports survey findings on students' knowledge and understanding of gene action within the cell. Understanding the genetic basis of cells was also the focus of the audiotaped group discussions, which are reported in Wood-Robinson *et al* (1997). Working Paper 2 (Lewis *et al*, 1997a) reports findings relating to students' understanding of basic genetics and DNA technology. All of the written probes produced for this part of the project - each one accompanied by a commentary on its use within this research project, a brief summary of the findings and suggestions for its use within the classroom - are published as a separate photo-copy free booklet (Lewis *et al*, 1997b).

Research questions 3 and 4 relate to students' awareness of issues raised by DNA technology and its applications, and their opinions and attitudes towards these issues. These were investigated through a second set of written probes and through two different audio taped group discussion tasks, led by an interviewer. Findings from the audio taped discussion tasks are reported in Working Paper 5 (Leach *et al*, 1996) and Working Paper 7 (Lewis *et al*, 1997c). Findings from the written probes are not yet available.

Those aspects of genetics which are taught in government funded secondary schools in England and Wales are defined by the National Curriculum. For the students involved in this study the version of Science in the National Curriculum which they had experienced was that published by the Department of Education and Science (DES 1991). Unless otherwise stated, all references to the National Curriculum within this paper relate to the 1991 National Curriculum for Science, Key Stages 3 and 4, Attainment Target 2 : Life and Living Processes. A new version of the National Curriculum has since been introduced (DfE 1995). Details of the design and methodology for the whole study, together with a discussion of the issues raised by the development of a science curriculum designed to increase scientific literacy within the general population and a discussion of genetics within the National Curriculum, are presented in Working Paper 1 (Wood-Robinson *et al*, 1996).

This paper (Working Paper 4) focuses on young peoples' knowledge and understanding of the genetic basis of cells and the genetic relationship between cells.

All the data presented in this paper were collected through a series of written questions to which students gave individual written responses. Almost 500 young people from across the ability range were surveyed for this part of the project. The majority of the sample had been taught genetics at Key Stage 4.

A review of the literature can be found in Working Paper 2 (Lewis *et al*, 1997a).

2 Design, Methodology And Administration Of The Written Probes

2.1 Design Of The Written Probes

As a first step in designing our written research probes we made a conceptual analysis of the areas covered by our first two research questions:

1. What knowledge and understanding of genetics do young people have at the end of their compulsory science education?
2. What knowledge and understanding of new genetic technologies do these same young people have?

In making this analysis we took into account both the requirements of the 1991 National Curriculum for Science at Key Stages 3 and 4 and also the background knowledge and understanding of genetics which an individual might need in order to develop a basic understanding of DNA technologies and the issues which the use of these technologies might give rise to. For a more detailed discussion of the conceptual analysis see Working Paper 1 (Wood-Robinson *et al*, 1996). Details of this analysis can be found in Appendix 1.

A preliminary investigation of students' knowledge and understanding of these key concepts was made using free response questions and small discussion groups. On the basis of this work a number of written research probes were produced, designed to cover as many of the conceptual areas as possible. These probes were piloted with almost 100 students of all abilities and evaluated for effectiveness, comprehension and timing. Finally, a revised set of 8 written probes - *Size Sequence, Living Things, Biological Terms, The New Genetics, Cells, Cell Division, Reproduction* and *Information Transfer* - were produced for the main study. Each of these probes were made up of two or more sections and each section often contained several related questions. The areas of our conceptual analysis covered by these eight probes are shown in Table 2.1. Many of these conceptual areas were covered by more than one probe, allowing us to assess the consistency of our findings across different contexts. Further details can be found in Appendix 2.

Only two of the conceptual areas which we listed were not covered in any way by these eight probes. Area *B2a* relates to possibilities and limitations in the application of DNA technology and is covered by a series of *'stop press'* probes which will be discussed in a future paper. Area *A5(ii)c* was not covered at all within this project. This area relates to the effect of selective pressures on gene frequencies and the gene pool - or more correctly, allele frequencies and the allele pool! When draft probes covering this area were trialled, students showed little awareness or understanding of it and gave very few meaningful responses. As the time available for collecting data from any individual was limited, we concentrated on those areas most likely to provide meaningful data and excluded this area from the probes.

Findings from the first four of these probes - *Size Sequence, Living Things, Biological Terms* and *The New Genetics* - were reported in Working Paper 2 (Lewis *et al*, 1997a). Findings from the remaining four probes - *Cells, Cell Division, Reproduction* and *Information Transfer* - are reported in this working paper.

Written questions requiring a written response were used in this part of the study as it allowed us to gather a large amount of data in a limited time. The main disadvantage in using pencil and paper probes, especially when our main interest was in conceptual understanding rather than content knowledge, was in the potential for misunderstanding. Not only were the students' responses open to misinterpretation by the researchers, there was also the potential for the researchers' questions to be misinterpreted by the students (see section 6.1.3). Preliminary work and piloting help to reduce this potential for misunderstandings but cannot overcome it.

Table 2.1 - Conceptual areas covered by the written probes

Conceptual Area	Specific Topic (see Appendix 1 for more details)	● Probes reported in Working Paper 2 ❍ Probes reported in this working paper
A: Genetics	A1a - basic genetics	● ●
A1. Terminology	A1b - range of organisms	●
A2. Location, Relationship between structures	A2a - genes/organisms	● ❍
	A2b - genes/cells	● ● ❍
	A2c - range	● ● ●
	A2d - site of mitosis	❍ ❍
	A2e - site of meiosis	❍
A3. Gene function	A3a - protein synthesis	● ●
	A3b - replication	● ❍ ❍
A4. Mechanisms and factors influencing gene expression	A4a - alleles	●
	A4b - environment	❍
	A4c - universal code	●
	A4d - mitotic cell division	❍ ❍ ❍
	A4e - meiotic cell division	❍ ❍
	A4f - fertilisation	❍
A5. Similarities and differences between cells	**i) within organism**	
	A5ia - somatic cells	❍ ❍
	A5ib - gene switches	❍
	A5ic - germ cells	❍ ❍
	ii) within species	
	A5iia - variation, germ cell	❍ ❍
	A5iib - variation, alleles	❍
	A5iic - variation, population	
	iii) between species	
	A5iiia - genetic information	●
	A5iiib - nucleic acids	●
	A5iiic - protein synthesis	●
	A5iiid - replication	❍
B: DNA technology	B1a - terminology	●
B1. Techniques	B1b - understanding	●
B2. Applications	B2a - real or potential	

Within the written probes, both fixed response and free response questions were used. Fixed-response questions can be answered relatively quickly and yield a large amount of data in a form which is easy to code and analyse. The disadvantage of this approach is that students must choose from a limited set of predetermined responses which may not reflect their own ideas very accurately. They do not have the opportunity to express their own ideas in their own words. This type of question gives limited insight into students' underlying reasoning or conceptual understanding. Free-response questions allow students to respond in their own way and in their own words, providing the researcher with a better insight into the students' underlying reasoning or conceptual understanding. However, free response questions take students longer to answer and the coding and analysis of responses is very time consuming. Whether fixed or free response questions are used, there is always a problem of misinterpretation. To validate findings from the written questions and to probe the students' reasoning in more depth, audiotaped small group discussion tasks were used (Wood-Robinson *et al*, 1997).

2.2 Administration

All eight *knowledge and understanding* written probes were presented as a single pack of questions which was administered to whole classes at one time. Because we wanted to collect data on the knowledge and understanding of individuals, students were asked to work on their own, without discussion with other members of the class. To encourage this, three different versions of the pack were produced. Each contained the same probes but in three different sequences, although all three versions began with *'Size Sequence'*. All three versions were administered within any one class with neighbouring students having different versions. As a result, individuals usually found that at any given time they were working on a different question from their neighbours. In addition this ensured that all probes were answered within each class, even if time was limited and individual students were unable to answer the whole pack. A further benefit of using three versions was that the same probes were not always answered last, when students might be bored or tired.

2.3 Sampling

The twelve schools from which data were collected for the main study were all co-educational comprehensive schools under local education authority control. They were drawn from the West Yorkshire region of England and covered a range of rural, urban and suburban catchment areas. 8 schools participated in this part of the project concerned with knowledge and understanding of genetics and DNA technologies. Within each of these schools the sample was drawn from across the ability range, with teachers selecting three classes - upper ability, middle ability and lower ability - to complete the probes. Altogether responses from 482 students in 24 classes were collected (see Table 2.2).

Our intention had been to work with a representative sample of the school population who had all completed the genetics component of their science education. In practice this proved difficult. Genetics is perceived to be difficult by some teachers and there is a tendency to leave this component of the syllabus until the end. In many schools there is little time between completion of the genetics component and commencement of GCSE exams, and researchers are not always welcome such a short time before public examinations. As a result it was impossible to collect an ideal sample in which all students had followed the genetics components of the National Curriculum programme of study. For the majority (72 % of this sample) teaching about genetics had been completed. The remaining 28% had been taught those areas of the curriculum which covered the structure and function of the cell, variation and its environmental and genetic causes, the transfer of information between generations in the form of genes and the basic principles of selective breeding. They had not completed work on cell division, the monohybrid cross (dominant and recessive relationships) or the molecular structure of genes (DNA replication, protein synthesis and the genetic code).

The levels of achievement within these schools, as measured by the percentage of A - C passes in GCSE sciences in the preceding year, ranged from 58% to 11.8%.

Using the DES Ethnic Monitoring Survey schools indicated their ethnic mix. Between 1% and 16% of the intake in these schools were from minority groups. These included students of Indian, Pakistani, Bangladeshi, Afrocaribbean and Chinese origin.

Table 2.2 - Survey sample, the *knowledge and understanding* pack

		number of students per class			
school	**year**	**upper ability**	**middle ability**	**lower ability**	**total**
1	11	16	15	14	45
3	11	29	22	11	62
7	11	15	18	11	44
8	11	26	25	24	75
9	11	29	24	22	75
10	11	23	13	12	48
12	11	31	24	12	67
13	10	26	21	19	66
	total	195	162	125	482

Of these 482 students -

- 416 (86.3%) were in Year 11 and aged 15 - 16,
  66 (13.7%) were in Year 10 and aged 14 - 15,

- 229 (47.5%) were female,
  253 (52.5%) were male,

- 351 (72%) had been taught most of the genetics specified in Key Stage 4,
  131 (28%) had been taught either very little or none of the genetics specified in Key Stage 4 at the time of the survey.

2.4 Coding And Analysis

Each fixed response question was scored according to the alternative ticked, with each alternative being given a code. The frequency with which each code was used was then determined.

Because our main interest was in the ideas and understandings which students used to explain particular situations rather than in the students' factual recall of taught knowledge we adopted an ideographic approach to coding the semi-structured and free response questions. Instead of developing a coding scheme based on the scientific explanation we developed a coding scheme based on the students' own responses. As the coding of a question progressed these schemes developed, through an iterative process of reconsideration and discussion, so that all types of response could be categorised. The coding schemes therefore represent the types of reasoning present within the population and as such, in addition to providing a means of analysing the data, they are an important research finding in themselves.

2.5 Reporting The Data

Not all students attempted to answer all the questions. In any one case it was not possible to know for sure if this was because the student couldn't answer the question, because the student didn't have enough time to answer the question or because of some other reason. As a result it was sometimes difficult to report key findings as a percentage of the total population (i.e. as a percentage of those asked the question). To overcome this, and to provide some consistency in reporting the data, the following criteria were used. If a student had attempted to answer some questions within a section of a probe (for example any of the four questions within the section on 'genes' in the *'Biological Terms'* probe, see Appendix 5a) but had not answered all the questions within that section then it was assumed that the student had read the questions but had been unable to answer some of them i.e. it was assumed that the student *had been asked* the questions. If a student did not respond to any of the questions within one section of a probe then it was assumed that the student had not had time to read and respond to that section i.e. it was assumed that the student *had not been asked* the questions.

Depending on the use that is being made of numerical data, they are presented either:

- as numbers,
- as a percentage of the total number of students responding to a specific question (i.e. as a percentage of those who attempted to *answer* the question),
- as a percentage of those who attempted that part of the probe (in effect, those who were *asked* the question),
- as a percentage of those who attempted some part of the whole probe.

Percentages are recorded as decimal numbers in the appendices but within the text they are rounded up or down to the nearest whole number for easier reading.

In presenting the data, ideas commonly held within the sample population are reported on. Ideas held by only one or two individuals are not. In most analyses there were also a small residue of unclassifiable responses - those which were ambiguous, incomprehensible or unreadable. In many cases the coding is not exclusive (one person may have expressed more than one of the listed views) therefore totals may add up to more than 100% at times.

Although data were collected at the individual level, they were analysed and reported at the population level. However, individual responses are sometimes used by way of illustration.

3 The *Cells* Probe

3.1 The probe

3.1.1 Design of the probe

This probe (see Appendix 3a) was designed to investigate students' understanding of the transfer of genetic information within an individual - that all somatic cells contain the same genetic information and that each sperm contains a unique combination of genetic information. It gives insights into students' understanding of the purposes of mitosis and meiosis and of the possibility of differential gene expression (that genes are switched on in response to a need for the gene product). It covers the following conceptual areas (see Appendices 1 and 2):-

A4 - mechanism of gene action (switches/codes/variation)

b: gene expression depends on environment (internal and external) to 'trigger' switches,

d: mitotic cell division (somatic cells; for growth) results in new cells containing identical numbers of chromosomes and exactly the same genetic information,

e: meiotic cell division (germ cells; for reproduction) results in new cells containing half the chromosome number and different genetic information (increases variation),

A5 - similarities and differences between cells

i) within one organism

b: different cell structure/function (somatic cells) is achieved by differential activation of genes (notion of gene 'switches') - see 4b,

c: germ cells contain different genetic information even though they are the same type of cell -see 4e,

ii) between organisms, within species

a: production of germ cells results in variation (see 4e/5ic); random combination of germ cells at fertilisation leads to even greater variation; the result is that cells from different organisms always contain different genetic information (exception = monozygous twins - they arise from the same fertilised egg),

b: alleles are the source of variation (in the gene product).

Awareness of these points has important implications for understanding of inheritance.

3.1.2 Structure of the probe

This probe consists of two parts. Part 1 was designed to probe students' understanding of the genetic relationship between cells within one individual. Students were asked to compare the genetic information in 4 pairs of cells from the same individual (a male). These pairs were:

- 2 somatic cells of the same type (cheek cells),
- 2 somatic cells of different types (a cheek and a nerve cell),
- 1 somatic cell and 1 germ cell (a cheek and a sperm cell),
- 2 germ cells (sperm cells).

Part 2 was designed to check the consistency of student's views, as expressed in Part 1 and Part 2, and to probe students' understanding of the difference between 'gene' and 'genetic information'. Students were asked to compare 2 somatic cells of the same type (cheek cells) from two different individuals, both male.

Each comparison followed the same format (see figure 3.1), beginning with a fixed response question and then asking for an explanation.

Figure 3.1 - Part of the *'Cells'* probe

Please answer the following questions by ticking ONE box.
Explain your reasons.

a) If you could take two of Robert's cheek cells would the genetic information in them be :-

Tick ONE Box

the same ☐

different ☐

don't know ☐

Please give the reasons for your answer - --

3.1.3 Critique of the probe

Part 1 of this probe was very effective in revealing the student's understanding of the genetic relationship between cells within one individual, providing that students responded to all 4 questions. It also allowed inferences to be drawn regarding the students' understanding of the purposes and products of cell division.

Part 2 was less effective in probing students understanding of the difference between 'gene' and 'genetic information'. While it exposed the inconsistency of many student's reasoning, it added little to our understanding of their reasoning. However, it would probably be an effective teaching tool, if used to alert students to the inconsistencies in their reasoning and to promote discussion of these.

It would have been interesting to ask about egg cells as well as sperm cells in Part 1, and to compare the student's responses. However, we could see no way of doing this, within this probe, without reducing the overall effectiveness of the probe. If we included a second set of questions, this time referring to a female, we were asking students to duplicate their responses to 3 of the 4 questions. If we simply added one extra question referring to egg cells, it didn't make sense in the context of the whole series of questions. A second set of questions, referring to a female, were included in the pilot but dropped from the final study due to the mixed response of students and the restrictions on time and space. Students could see no reason for being asked what they perceived to be a duplicate set of questions and this affected their attitude toward completing them. This perception also had some effect on how they felt about completing the pack of questions as a whole, especially as a similar problem arose in the *'Cell Division'* probe, with many students failing to recognise that the first set of questions referred to mitosis and the second set referred to meiosis.

While a comparison between a male and a female in Part 2 would have brought out ideas relating to sex differences it would have made the analysis difficult.

3.1.4 Coding and analysis of the probe

Our interest was in the student's understanding of the continuity of genetic information within and between generations. For this reason the pattern of responses to all four questions in Part 1 was as important as the frequency of responses to individual questions.

In the first instance, responses to each of the 5 questions were coded and the frequency of different responses noted (see Appendix 3b).

A second analysis was then made, based on responses to all four questions in Part 1. To avoid making assumptions about the student's pattern of thinking, only those cases in which the student had given an explicit tick response (either 'same' or 'different') to all four questions were included (see Appendix 3c).

3.2 Analysis of the data

Our sample size for this probe was 478 (99% of those taking part). For a breakdown of exact numbers responding to each part of the probe see Appendix 3b.

3.2.1 Comparison of genetic information within an individual

All students responding to this probe attempted Part 1 but only 290 (61%) gave an explicit ticked response to all 4 questions. The majority of these seemed to hold a clear and consistent (although not necessarily correct) view of the nature of genetic information within different cells in an individual. Their views appeared to stem from one of three basic premises:

- that all cells contain the same genetic information ;
- that all cells contain different information
  (in some cases they seemed to be suggesting that information from the fertilised egg was shared out at each cell division) or
- that each type of cell contains just that information which it needs in order to perform its function.

The most frequent premise (172; 59% of this group) was that each type of cell contains just that information which it needs in order to perform its function.

While one third of this group (99; 21% of the sample) made some distinction between somatic and sperm cells, only 20 (4% of the sample) correctly recognised that all somatic cells carry the same genetic information, regardless of function, that sperm cells do not carry the same genetic information as somatic cells and that each sperm cell carries a different combination of genetic information. The majority (171; 59% of this group) made no distinction between somatic and sperm cells. A small number (20; 4% of the sample) held inconsistent ideas that were confused or contradictory. A summary of these findings can be found in Table 3.1

Table 3.1 - understanding the relationship between genetic information in different cells of the same individual

	Basic premise concerning the genetic information in cells		
Responses	**1. same** (n = 56)	**2. different** (n = 42)	**3. function related** (n = 172)
do not distinguish between somatic and sperm cells	9.6% [28; 5.8%]*	9.6% [28; 5.8%]	39.6% [115; 23.9%]
do distinguish between somatic and sperm cells	2.7% [8; 1.7%]	4.8% [14; 2.9%]	19.6% [57; 11.8%]
correctly distinguish between somatic and sperm cells	6.9% [20; 4.1%]	-	-
give contradictory explanations	6.9% [20; 4.1%]		

number of students asked - 478
number giving 4 explicit responses - 290 (61%)
* [28; 5.8%] denotes n = 28; which corresponds to 5.8% of the whole sample

The remaining 188 responses included one or more responses of '*don't know*'. Of these, one quarter (41; ~9% of the sample) showed no discernible reasoning and appeared to have no idea about the genetic relationship between cells. The remainder (147; 31% of the sample) expressed a range of different ideas but seemed to lack a coherent line of thinking which could explain all cases.

Lines of thinking found in responses to Part 1 are illustrated in Table 3.2 and summarised in Appendix 3c. Further details of these findings, including written responses to individual questions, can be found in Appendix 3b.

3.2.2 Comparison of genetic information between two individuals

475 students responded to Part 2 of the probe and the majority view (407; 86% of the sample) was that genetic information in two cheek cells from different individuals would be different.

While most students were well aware that no two individuals (with the exception of identical twins) carry exactly the same genetic information this view conflicted, for many, with their reasoning in Part 1 - that each type of cell contains just that genetic information which is required to carry out its function.

Table 3.2 - An illustration of different lines of thinking using student's full written responses

student 7111.14

Correctly distinguishes between somatic cells and gametes (sperm cells).

comparison	response	reason
cheek:cheek	same	*'because all of his cells contain the same genetic information, only different bits of the information is used in different cells'*
cheek:nerve	same	*'as before, all of his cells contain the same information, but different parts of it are used in his nerve cells'*
cheek:sperm	don't know	*'the sperm cell would only contain half the information because it is a gamete, but that information may be the same as in a half of one of his other cells.'*
sperm:sperm	different	*'because sperm cells only contain half the chromosomes of the other cells, it is 'chance' which decides which information is in which sperm cell.'*

student 8111.25

Consistent and explicit view that genetic information is related to function; no distinction between somatic and germ cells.

comparison	response	reason
cheek:cheek	same	*'because they remember what he is like and what shape to turn so they all need to be the same'*
cheek:nerve	different	*'because the cheek cells need to know how to form cheek cells and the nerve cells need to be able to form nerve cells'*
cheek:sperm	different	*'same as previous'*
sperm:sperm	same	*'because all types of cells which are the same (e.g. sperm cells) contain the same information'*

student 12111.25

Conflict between 'all cells carry the same information' and 'genetic information is related to function'; no distinction between somatic and germ cells.

comparison	response	reason
cheek:cheek	same	*'because they are from the same person and all the genetic information is the same'*
cheek:nerve	different	*'because they contain info on that part of the body and it is no good the nerves having cheek cell info'*
cheek:sperm	same	*'because the sperm carries all the genetic information so it would contain the cheek cells'*
sperm:sperm	same	*'because they are from the same person'*

student 7112.09

Conflict and confusion: basic view appears to be that genetic information is related to function, but also considers all cells to carry the same information; confused between gene and chromosome (leading to concept of male and female genes?).

comparison	response	reason
cheek:cheek	same	*'has 2 genes and therefore all cells carry the same information'*
cheek:nerve	different	*'both have different functions'*
cheek:sperm	different	*'both have different functions (partly the same?)'*
sperm:sperm	same	*'both contain information on male and female genes. Not sure if egg and sperm have male and female gene - think egg has female and sperm has both'*

There was little recognition of this conflict. Only 7 responses (less than 2% of the sample) clearly recognised the conflict and tried to resolve it:

> *'Although they are both the same type of cell they would contain different information to produce different cheeks'*
>
> student1111/2
>
> *'They are two different people. Though some information would probably be the same.'*
>
> student 3111/15
>
> *'The cells are a different size and from different parents and would therefore contain different information.'*
>
> student 3111/18

A further 19 responses (4% of the sample) were ambiguous but could have been interpreted as recognising and trying to resolve the conflict:

> *'They're two different people with two different cheeks.'*
>
> student 3111/14
>
> *'Because they are different people they will have different face shape so the cells will be adapted in different ways'*
>
> student 3112/1

The majority (249; 52% of the sample) simply maintained that different people have different genetic information. A further 90 responses (19% of the sample) also expressed this view but gave a justification based on differences in parents, sperm, cell nucleus or DNA.

Just 7 responses (less than 2% of the sample) explicitly distinguished between genes and genetic information in their reasoning:

> *'They don't have the same information because the cells both need to do the same jobs but will have different alleles causing different reactions'*
>
> student 1111/7

Of the 10 students who said that the genetic information would remain the same the most common justification (5; ~1% of the sample) was that cells of the same type would need the same information.

3.3 Discussion of results

From this analysis of the *'Cells'* probe it is clear that a substantial proportion of this sample had no coherent view of the genetic relationship between cells, within one individual. One possible explanation is that teaching had led to a fragmentary knowledge of 'facts' but had not provided a conceptual framework which could explain these facts. Without such a framework it was difficult for these students to make sense of ideas which were counter intuitive. Even amongst those who did hold a coherent and consistent view, the proportion showing a scientifically correct understanding was very small. The majority made no distinction between somatic and sperm cells and the most common view was that genetic information within a cell is determined by the structure, function or even position of that cell.

These findings, which were supported by interview data (Wood-Robinson *et al*,1997), suggest that students in this sample had a very poor understanding of the purposes, processes and products of cell division and made little distinction between mitosis and meiosis. Their previously documented difficulties with the concepts of *gene* and *chromosome* (Lewis *et al*, 1997a) might account for this. These included:
- a general uncertainty about the nature and role of chromosomes;
- confusion about the relationship between chromosomes and genes and, in particular,
- a failure to recognise that a gene has a specific physical location on a chromosome.

Given this uncertainty and confusion about genes and chromosomes it is difficult to see how these students *could* recognise the implications of cell division - that as chromosomes replicate, genes replicate; that when the new cell receives a copy of the chromosomes it also receives a copy of each gene on those chromosomes; that as a result, each new somatic cell must contain the same genetic information as the parent cell. Without these basic concepts, and in the absence of any notion of gene 'switches' - the idea that genes can be switched on or off according to need - the idea that cells with different structures and functions should have the same genetic information is counter intuitive.

It was also clear from this analysis that few students understood the distinction between a gene (a length of DNA at a specific location on the chromosome) and the genetic information encoded within that gene (which determines the precise nature of the gene product). Without this understanding it is difficult to see what concept of alleles these students might have, or how they might understand the genetic determination of characteristics.

It is generally recognised that many students find the topic of inheritance difficult (Wood-Robinson, 1994). On the evidence presented here this is not surprising. Their limited understanding of the basic concepts underpinning this complex concept would make it difficult for them to develop a coherent explanation of the whole.

4 The *'Cell Division'* Probe

4.1 The probe

4.1.1 Design of the probe

This probe (see Appendix 4a) was designed to investigate student's understanding of the functions, processes and products of cell division and their understanding of the distinction between mitosis and meiosis - that mitosis results in new somatic cells containing the same number of chromosomes and the same genetic information as the parent cell; that meiosis results in the production of gametes with only half the usual number of chromosomes and with different genetic information. It also probes their awareness that these processes are common to both plants and animals. It covers the following conceptual areas (see Appendices 1 and 2):-

A2 - location (relationship between structures)

d) site of mitosis (somatic cells),

e) site of meiosis (germ cells),

A3 - function of genes

b) genetic information must be copied to pass on to new cells during cell division,

A4 - mechanisms of gene action

d) mitotic cell division (somatic cells, for growth) results in new cells containing identical numbers of chromosomes and exactly the same genetic information,

e) meiotic cell division (germ cells, for reproduction) results in new cells containing half the chromosome number and different genetic information (increases variation),

A5 - similarities and differences between cells

iii) between species

d) genetic information is copied and passed on during cell division in all organisms.

4.1.2 Structure of the probe

This probe consists of two parts. Part 1 was designed to investigate student's understanding of mitosis through a consideration of the production of skin cells and Part 2 was designed to investigate student's understanding of meiosis through a consideration of the production of an egg cell. Each part followed a similar format and used a mix of free and fixed response questions (see Appendix 4a). Students were asked to:

- compare chromosome number and genetic information in the original and the new cell (see figure 4.1);
- identify where, in the body, this type of cell division takes place;
- say whether or not such cell division also occurs in plants.

4.1.3 Critique of the probe

Originally a more open format was used, in which students were asked to draw in the chromosomes which the new cell would contain. Many students found this difficult to do and as a result the fixed format was adopted. In doing this we limited the range of ideas that we might uncover, but increased the sample size. A few students drew chromosomes into the empty cells instead of (or as well as) giving a tick response. These were ignored for the purpose of analysis.

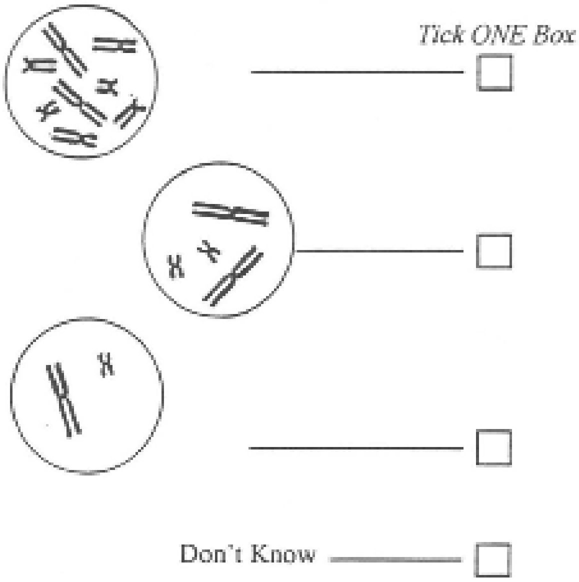
Students' lack of awareness of the two types of cell division sometimes presented problems in Part 2, which they perceived to be a straight repeat of Part 1. In these cases they were directed to re-read the introductory sentences to each part, which explicitly referred to skin cells in Part 1 and egg cells in Part 2.

The range of confused and ambiguous responses that were produced made coding the free response sections difficult. Despite this it was possible to pick out a number of ideas with reasonable certainty.

Figure 4.1 - part of the *'Cell Division'* probe relating to chromosome number in skin cells

If the original skin cell contained the chromosomes shown in the diagram above, what chromosomes do you think the new skin cells would contain?

Look at the diagrams below and tick ONE box to show which chromosomes you think would be found in the NEW SKIN CELLS.
Please give reasons for your answer.



Reason- --

4.1.4 Coding and analysis of the probe

For each fixed response question in Part 1, the frequency of responses to each option was noted. The types of reasoning used to justify each option, and the frequency with which they were used were then recorded. To gain a more complete insight into the student's understanding of mitosis, tick responses to the question on chromosome number were compared with tick responses to the question on genetic information using crosstabs. Tick responses relating to the location of mitotic cell division were grouped according to whether somatic cells only, germ cells only or a mixture of both were ticked and these new groupings were used in the subsequent analysis. The same process was repeated for Part 2 (meiosis). Details of this coding can be found in Appendix 4b.

While this analysis gave insights into the students' understanding of each process, it gave no indication of their understanding of the difference between the two processes. For this purpose a second analysis of the date was made. Responses to fixed response questions in Part 1 were compared with responses to the same fixed response questions in Part 2, using crosstabs (see Appendix 4c).

4.2 Analysis of the data

Our sample size for this probe was 481. The proportion of students who didn't know or didn't attempt any one question within this probe varied but was never more than 31% (see Table 4.1). This suggests that this population of students felt reasonably comfortable with, and confident about, the concept of cell division - a suggestion which is supported by the reasonably high proportion of students who gave reasons for their response. This confidence was not a reflection of the extent to which they understood the science (see sections 4.2.1 - 4.2.3). Overall, questions relating to meiosis generated fewer explicit responses and fewer reasons for those responses than did questions relating to mitosis. The main types of reasoning about specific aspects of mitosis and meiosis, and an analysis of the student's understanding of the general principles of mitosis and meiosis, are given under separate sub-headings below.

Table 4.1 - breakdown of responses to questions on cell division

	Types of Response		
Questions:	didn't know or didn't answer	gave an explicit tick response	gave a reason for their response
Part 1: Mitosis			
a) chromosome number	80 (17% of sample)	401 (83% of sample)	362 (90% of responses)
b) genetic information	100 (21% of sample)	377 (79% of sample)	328 (87% of responses)
c) location	76 (16% of sample)	405 (84% of sample)	not requested
d) occurrence in plants	35 (7% of sample)	446 (93% of sample)	330 (74% of responses)
Part 2: Meiosis			
a) chromosome number	151 (31% of sample)	330 (69% of sample)	277 (84% of responses)
b) genetic information	140 (29% of sample)	341 (71% of sample)	263 (77% of responses)
c) location	111 (23% of sample)	370 (77% of sample)	not requested
d) occurrence in plants	65 (14% of sample)	416 (86% of sample)	277 (67% of responses)

For a breakdown of the exact numbers responding to each part of this probe, and for a more detailed analysis of the student's reasoning, see Appendix 4b.

4.2.1 Understanding of mitosis

a: chromosome number

There were 401 explicit tick responses to the question *'How many chromosomes would be found in the new skin cells?'* of which 90% gave reasons for their response (Table 4.2).

Table 4.2 - reasoning related to chromosome number in the new skin cell

chromosome number	main lines of reasoning	number giving this reason	% of those giving this response
8 responses: n = 101; % = 25	• confusion - about the terminology • confusion - cell or chromosome? • depends on age/health of cell	26 26 11	26 26 11
4* responses n = 220; % = 55	• compatible with the science: chromosomes copied/shared • cells of same type/function	93 80	42 36
2 responses n = 80; % = 20	• chromosomes shared (but not replicated)	43	54

* *correct response*

Over half the tick responses were correct - chromosome number would remain the same. However, the justifications for this were not always compatible with the scientific view. Over one third of those giving this response said that the chromosome number would remain the same because the cells were of the same *type* (skin cells). A number of other responses were ambiguous.

Amongst those who said that the chromosome number would double, there was considerable confusion. One quarter seemed unable to distinguish between cell and chromosome. A further quarter were confused by the terminology ('splitting' and 'copying' for example) and unsure which structures these terms referred to (cells or chromosomes):

> *'because cells divide, making twice as many as you had before'*
>
> student 13101/10

The original question referred to 'new' cells and one in ten of these responses suggested that young, healthy cells would have more chromosomes than old or unhealthy cells:

> *'because the skin cells are new and young and so have more chromosome'*
>
> student 8112/8
>
> *'because the chromosomes will eventually start to die so the number will start to reduce'*
>
> student 8113/15

More than half of those who thought that the chromosome number would halve understood that chromosomes are shared out at cell division but seemed to be unaware that they are copied first:

> *'This is half of the original skin cell'*
>
> student 9111/4
>
> *'The new cell will divide the old cell into two and take half of its cell'*
>
> student 8112/6

b: genetic information

There were 377 explicit tick responses to the question *'Would the new skin cell and the original skin cell contain the same or different genetic information?'* of which 87% gave reasons for their response (Table 4.3).

Table 4.3 - reasoning related to genetic information in the new skin cell

genetic information	main lines of reasoning	number giving this reason	% of those giving this response
the same* responses: n = 312; % = 83	• new cell is copied from original cell • *all* cells contain the same genetic information • new cell is of the same type	110 43 51	35 14 16
different responses: n = 65; % = 17	• depends on age/health of cell	9	14

* *correct response*

The majority gave the correct response - that the genetic information in the two cells would be the same. Again, their reasoning was not always compatible with the scientific view, but in this context the differences were less clear cut. The most frequent justification was that the new cell was copied from the original cell. This could be taken to reflect a scientific view of mitotic cell division but, equally, it might include those who held the view that cells of the same type contain the same genetic information. Fewer than one sixth of those giving this response explicitly stated that *all* cells would contain the same genetic information. Even amongst this group a correct scientific understanding could not be assumed. Several responses suggested that all cells contain the same information even if the number of chromosomes varies:

> *'it would carry the same* [genetic information] *but would have less chromosomes in the new skin'*
>
> student 7112/17

There was no evidence to suggest that this group understood that cells produced by meiosis would have different information. There was some confusion between genetic information and the genetic code:

> *'The genetic code would be the same it would just contain more chromosomes'*
>
> student 8112/17

About one sixth explicitly stated that genetic information would be the same because the cells were of the same type.

Of those who held the opposite view - that the genetic information would be different in the new skin cell - reasoning was diverse or absent in many cases. The most common view was that genetic information depends on the state of the cell (age or health). This was often linked to the number of chromosomes:

> *'they will contain the same genetic information because the new skin cells will have less chromosomes'*
>
> student 13102/18

Confusion over the terminology of cell division (split, divide, multiply) was again apparent.

c: location of mitosis

There were 405 explicit responses to the question *'Which of the following parts of the body would divide in this way?'*. Responses, grouped with reference to somatic tissues and/or gonads, are shown in Table 4.4. Students were not asked to give reasons for their response to this question.

Table 4.4 - location of mitosis

location	number of responses	% of explicit responses (n = 405)	% of the sample (n = 481)
somatic tissues only*	140	35	29
gonads only	102	25	21
mixture of both	163	40	34

** correct response*

Responses were relatively evenly divided between the three categories. One third correctly suggested that mitosis only took place in somatic tissues but no reasons were asked for and it cannot be assumed that all of these students understood the science correctly. Slightly more suggested a mix of somatic tissues and gonads and a further quarter suggested gonads only.

d: mitotic division in plants

There were 446 explicit tick responses to the question *'Does the same type of cell division, for the same purpose, occur in plants?'* of which 74% gave reasons for their responses (Table 4.5).

Table 4.5 - reasoning related to mitotic cell division in plants

occurrence in plants	main lines of reasoning	number giving this reason	% of those giving this response
yes* responses: n = 299; % = 67	• plants are living, like animals • there is no other type of cell division in plants	157 6	53 2
no responses: n = 147; % = 33	• plants are not like animals • plants are not living	64 2	44 1

** correct response*

Two thirds of the responses correctly indicated that mitotic cell division also occurs in plants and the main justification for this view was that plants are living, just like animals. Some clearly understood the biological basis of this:

> *'Plants also contain cells with living chromosomes'*
>
> student 13103/9

'Because they [plants] *would not stop growing'*

student 13101/8

'Because if the cells had less than the chromosomes the original cell had they would lack some genetic information'

student 12111/19

A few responses showed confusion with reproduction and a small number stated that no other type of cell division was possible in plants but the majority of these responses were ambiguous. Most of these students appeared to be puzzled by the question and to be wondering what other types of cell division there might be:

'because there is no other way they can divide?'

student 9111/7

'The plant cells are produced by plants. This is about the only way this can happen.'

student 9111/23

Of those who did not believe that mitotic cell division occurred in plants the majority of responses suggested that plants were not like animals. In two cases the responses were quite explicit - plant cells do not divide:

'Cells in plants are rigid so they cannot divide'

student 9112/20

'Bulbs divide (I have seen double bulbs)'

student 10111/11

Two individuals did not consider plants to be living.

4.2.2 Understanding of meiosis

a: chromosome number

There were 330 explicit tick responses to the question *'How many chromosomes would be found in the egg cell?'* of which 84% gave reasons for their response (Table 4.6)

Table 4.6 - reasoning related to chromosome number in the egg cell

chromosome number	main lines of reasoning	number giving this reason	% of those giving this response
8 responses: n = 72; % = 22	• confusion: processes and structures • confused meiosis with fertilisation • sex cells need more chromosomes	13 7 10	18 10 14
4 responses: n = 110; % = 33	• no differentiation between somatic and germ cells	63	57
2 responses: n = 148; % = 45	• chromosomes are split or shared equally • confused about the role of sex chromosomes	69 9	48 6

* *correct response*

Almost one half of the responses correctly stated that the egg would contain half the number of chromosomes. The most common justification for this was that chromosomes are split or shared equally during cell division. More than half of these responses (40) explicitly mentioned the need for a reduction division in preparation for fertilisation:

> *'If they both had two sets of each in the sperm and the egg then they're child would have double of everything'*
>
> student 9113/4

However it is possible, given the findings from other probes (e.g. the *'Cells'* probe), that some students giving this justification made no distinction between mitosis and meiosis and thought that all cell divisions resulted in an equal sharing of chromosomes. There was some confusion about the role of sex chromosomes in this process:

> *'Egg cells have only two chromosomes (XX)'*
>
> student 10111/15

> *'The egg cell would only have two chromosomes in it to say whether the baby would be a girl or a boy'*
>
> student 13101/10

Of those who said that the number would stay the same, the majority appeared to make no distinction between somatic and germ cells. Some students appeared to be confusing the process of egg production with the processes of fertilisation.

Of those who thought that the chromosome number would double, the majority appeared to be confused - some by the processes (copying and splitting) and/or structures (cell and chromosome) of cell division others with the process of fertilisation:

> *'When a cell divides its chromosomes double'*
>
> student 10111/14
>
> *'The cells* [referring to chromosomes] *multiply by meiosis'*
>
> student 1111/15

> *'It's got bigger - chromosomes form 2 cells (M and F) join together'*
>
> student 9112/23
>
> *'the sperm chromosomes have joined the egg'*
>
> student 13101/18

Some students had a clearly held belief that sex cells contained more chromosomes than somatic cells. As one explained:

> *'There are more chances of the chromosome being passed on to the new child* [-] *if one is produced'*
>
> student 9112/4

A more typical explanation was:

> *'These chromosomes come from your body and will contain the same number as in the original cell because this is how your baby looks like you'*
>
> student 13101/24
>
> *'There is a possible human inside the egg'*
>
> student 8112/14

b: genetic information

There were 341 explicit responses to the question *'Would the egg cell and the original cell contain the same or different genetic information?'* of which 77% gave reasons for their response (Table 4.7).

Table 4.7 - reasoning related to genetic information in the egg cell

genetic information	main lines of reasoning	number giving this reason	% of those giving this response
the same responses: n =178; % = 52	• all new cells contain a copy of the original information	60	34
	• the genetic information is related to cell function	18	10
	• egg cells contain all the information for the next generation	9	5
	• genetic information cannot be changed	7	4
different* responses: n = 163; % = 48	• made link with variation in offspring	74	45
	• the genetic information is related to cell function	6	4
	• confused meiosis and fertilisation	13	8

* *correct response*

Just under one half of these responses correctly recognised that the genetic information in the egg cell would be different. Of these, the most common justification was a recognition that each egg cell needs different genetic information if there is to be variation in the offspring. About half of these responses explicitly refer to the processes which give rise to variation:

> *'Because the DNA during meiosis becomes different because the DNA strands swap over.'*
>
> student 8112/14

The argument that the genetic information will depend on the type or function of the cell was used to justify both types of responses. In a way it is reasonable to argue that in egg cells, because of their very specific function, genetic information is related to function. However, most of those giving this type of reason seemed to be suggesting a more generally applicable rule.

In a number of cases there appeared to be confusion between the process of fertilisation and the process of meiosis.

Of those who maintained that the genetic information would remain the same, a few stated explicitly that genetic information could not be changed. This suggests a lack of understanding about the processes and products of meiosis and a confusion between changing the information in the DNA and re-assorting and sharing out that information during meiosis.

c: location of meiosis

There were 370 explicit responses to the question *'Which of the following parts of the body would divide in this way?'* (see Table 4.8).

Table 4.8 - location of mitosis

location	number of responses	% of explicit responses (n = 370)	% of the sample (n = 481)
somatic tissues only	71	19	15
gonads only*	119	32	25
mixture of both	180	49	37

* *correct response*

The most common view was that meiosis occurred in both types of tissue but almost one third of those responding (one quarter of the whole sample) recognised that meiosis only took place in the gonads.

d: meiotic division in plants

There were 416 explicit tick responses to the question *'Does the same type of cell division, for the same purpose, occur in plants?'* of which 67% gave reasons for their response (Table 4.9).

Table 4.9 - reasoning related to meiotic cell division in plants

occurrence in plants	main lines of reasoning	number giving this reason	% of those giving this response
yes* responses: n = 212; % = 51	• plants are living, like animals	100	47
no responses: n = 204; % = 49	• plants are not like animals	97	47

* *correct response*

Responses appeared to be equally divided as to whether or not meiosis occurs in plants and the same type of reasoning, based on the extent to which plants and animals are similar, was used to the same extent by both groups. The two groups also showed a similar level of uncertainty and confusion with the majority in each case either unable to give reasons or giving a range of confused reasons.

Of those who said that meiosis did occurred in plants, because plants are like animals, the majority referred explicitly to sex cells and/or the process of reproduction:

'Plants grow seeds which are similar to sex cells'

student 10113/13

It is likely that those who were less explicit included some who did not distinguish between mitosis and meiosis and who used the same line of argument in each case.

Of those who said that meiosis did not occur in plants, because plants are not like animals, the most frequent justification was that there is no sexual reproduction in plants:

'Plants grow from roots, they don't mate together'

student 13102/15

Others suggested that there was sexual reproduction, but it was somehow different:

'Plants don't make contact when reproducing so the way the plant reproduces is down to the way it is contacted'

student 10113/8

4.2.3 Understanding of the differences between mitosis and meiosis (a comparison of responses to mitosis and meiosis)

a) on the basis of chromosome number

When responses to the fixed response question on chromosome number were compared, 59% of the sample appeared to recognise that there was some difference between the two types of cell division, but many were unclear what that difference might be. This was reflected in the proportion who appeared to distinguish correctly between mitosis and meiosis compared with the proportion who gave the correct response in relation to one type of cell division (usually mitosis) and a different, but incorrect, response in relation to the other type of cell division (see Table 4.10).

29% made no distinction between mitosis and meiosis on the basis of chromosome number in the new cell.

Table 4.10 - comparison of responses to the question on chromosome number

	number giving this response	% of the sample (n = 481)
make no distinction between mitosis and meiosis (gave the same response in both cases)	140	29
correct for mitosis but not for meiosis	134	28
correct for meiosis but not for mitosis	62	13
correctly differentiated between mitosis (4C) and meiosis (2C)	86	18
'didn't know' or didn't respond	55	11

b) on the basis of genetic information

When responses to the fixed response question on genetic information were compared the proportion of the sample who appeared to distinguished between the two types of cell division dropped to 39% but a greater proportion of these appeared to distinguish correctly between mitosis and meiosis (see Table 4.11).

Almost one third made no distinction between mitosis and meiosis on the basis of genetic information in the new cell.

Table 4.11 - comparison of responses to the question on genetic information

	number giving this response	% responding to this probe (n = 481)
make no distinction between mitosis and meiosis (in both cases information will be the same)	145	30
correctly differentiate between mitosis (same) and meiosis (different)	106	22
'didn't know' or didn't respond to both questions	66	14
correct for mitosis but didn't know for meiosis	61	13
correct for meiosis but didn't know for mitosis	17	4

c) on the basis of location

When responses to the fixed response question on location were compared, 36% appeared to make some distinction between the two types of cell division but this time a greater proportion of these gave the correct response in relation to just one type of cell division (usually mitosis) and a different, but incorrect, response in relation to the other type of cell division (see Table 4.12). Of those who made a clear distinction between mitosis and meiosis on the basis of tissue type, about one sixth reversed the location, placing meiosis in the somatic tissues and mitosis in the gonads.

11% located all cell division in just one type of location - either somatic tissues or gonads. This group appeared to recognise that there was an important distinction between gonads and somatic tissue in terms of cell division but unclear about the nature of that difference - perhaps because they made no distinction between the two types of cell division. A further 19% made no distinction between mitosis and meiosis or between somatic tissues and gonads.

34% of the sample either didn't know where either type of cell division took place or showed no discernible pattern of responses.

Table 4.12 - comparison of responses to the question on location

	number giving this response	% of the sample (n = 481)
clearly distinguished between mitosis and meiosis on the basis of tissue type	79	16
no distinction between mitosis and meiosis or somatic tissues and gonads	89	19
correct for mitosis but unsure about meiosis	71	15
correct for meiosis but unsure about mitosis	26	5
distinguished between gonads and somatic tissues but not between mitosis and meiosis	51	11

d) on the basis of their response to plants

34% of the sample seemed to recognise that both types of cell division occur in plants. However, given the levels of confusion about the processes of mitosis and meiosis evident in response to other questions, what this means in terms of these student's understanding is open to question. It cannot be assumed to reflect a good scientific understanding.

For similar reasons it is difficult to know how to interpret the finding that 22 % of the sample believe that mitosis is the only type of cell division that occurs in plants and 8% believe that only meiosis occurs in plants.

The negative finding is less ambiguous. 18% of this sample do not appear to believe that either type of cell division occurs in plants. This raises further questions. Do these students think that there is some other form of cell division in plants? There is no evidence to suggest this. If they do not believe that any form of cell division takes place in plants, how do such students explain growth and what understanding do they have of cells?

Table 4.13 - comparison of responses to the question on

	number giving this response	% responding to this probe (n = 481)
both types of cell division occur	165	34
only mitosis occurs in plants	107	22
only meiosis occurs in plants	40	8
neither division occurs in plants	88	18

4.3 Discussion of results

Despite the willingness of these students to respond to both the fixed and the free response questions in this probe, their actual understanding of cell division appears to be very limited and confused.

The belief that the genetic information in a cell is determined by the type or function (or even the location or appearance) of the cell was again evident, as was the idea that genetic information is shared but not copied at cell division. Similar ideas where also held in relation to chromosome number, but reasoning about both genetic information and chromosome number was not always consistent.

There was generally a lack of awareness of the relationship between chromosomes and genetic information, as evidenced in the comparison of genetic information and chromosome number in the new cell (see Table 4.14 a - c). While the majority of students seemed to be aware that there was some difference between mitosis and meiosis, most were unclear as to the nature of that difference in terms of either chromosome number or genetic information (Table 4.14c).

Table 4.14 - understanding of mitosis and meiosis

a) mitosis: comparison of new skin cell and original skin cell

comparison of:	correct response (%) *C = 4* *information = same*	alternative view (%) *C = 8 or 2* *information = different*	don't know (%)
a) chromosome number	46	37	17
b) genetic information	65	14	21
c) both	40	-	-

b) meiosis: comparison of egg cell and original cell

comparison of:	correct response (%) *C = 2* *information = different*	alternative view (%) *C = 8 or 4* *information = same*	don't know (%)
a) chromosome number	31	38	31
b) genetic information	34	37	39
c) both	14	-	-

c) ability to distinguish between mitosis and meiosis

on the basis of:	correctly distinguish (%)	make no distinction (%)	other responses* (%)
a) chromosome number	18	29	53
b) genetic information	22	38	40

* *10% were unable to say anything about either type of cell division in terms of chromosome number*
13% were unable to say anything about either type of cell division in terms of genetic information

A small proportion of the sample consistently related chromosome number or genetic information to the state of the cell - its age or health. This may have been as a result of the wording of the questions, which referred to the 'new' cell (to distinguish it from the original cell).

Of those students who were aware that chromosomes were copied during cell division some thought that replication only occurred after the chromosomes had been shared out and the cell had divided. This clearly limits their ability to understand the continuity of genetic information between cells.

The proportion of students clearly showing a good understanding of the science ranged from 10 - 25% depending on the particular question. This lack of consistency across questions suggests that even when these students understood some aspects of the cell division, they had no coherent conceptual framework which could explain the whole set of processes.

There was widespread confusion about the different aspects of cell division. In many cases it was difficult to identify the source of that confusion but a number of common factors did emerge. A major issue was terminology. In the absence of a coherent conceptual framework students were confused by the words used to describe the processes of cell division - replicating, dividing, copying, splitting, multiplying, sharing - which could appear contradictory. Their difficulty with these words was often compounded by their inability to differentiate clearly between chromosomes and cells. They appeared to be unclear as to when the words were being applied to cells and when they were being applied to chromosomes. Some students were confused by the similarity of the two words - mitosis and meiosis. This was apparent when students clearly understood one of the differences between the two processes but attributed it to the wrong type of cell division (Section 4.2.3c). Many students seemed to be unaware that there were two types of cell division. In some cases this was evident in their failure to make any distinction between meiosis and mitosis on the basis of chromosome number, genetic information or location. In other cases they seemed to make a distinction between mitosis and meiosis but only recognised mitosis as cell division. Meiosis appeared to be linked with reproduction and confused with fertilisation.

It is difficult to see how students with such a limited understanding of the purposes, processes and products of cell division can understand the continuity of genetic information within individuals and between generation - or how they might make sense of inheritance.

These findings also raise a further question - what do these students understand by 'cell'?

5 The '*Reproduction*' probe

5.1 The probe

5.1.1 Design of the probe

This probe (see Appendix 5a) was designed to investigate student's understanding of the processes by which genetic information is transferred to a new individual. It covers the following conceptual areas (see Appendices 1 and 2):-

A4 - mechanisms of gene action

f) fertilisation gives continuity (genetic information passes from parents to child) and variation (mixing of alleles),

A5 - similarities and differences between cells

ii) within species

a) production of germ cells results in variation (see 4e/5ia); random combination of germ cells at fertilisation leads to even greater variation; as a result the cells from different organisms always contain different genetic information (exception: monozygous twins - they arise from same fertilised egg),

iii) between species

d) genetic information is copied and passed on during cell division in all organisms.

5.1.2 Structure of the probe

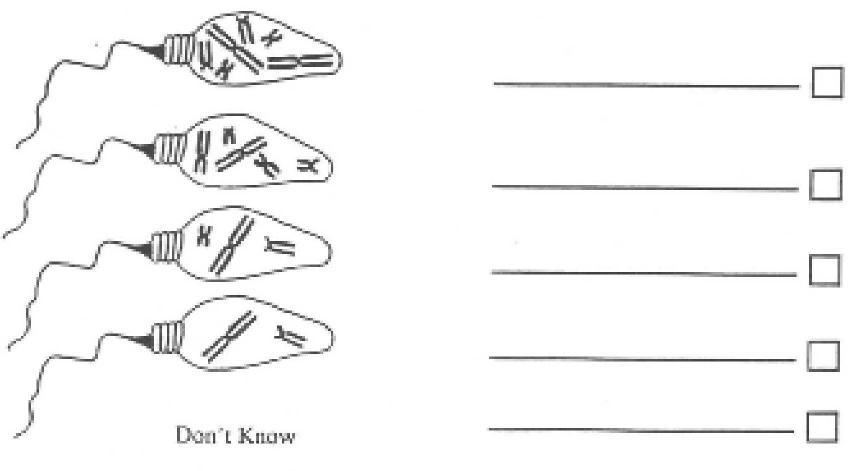
This probe was in three parts. Part 1 was designed to investigate student's understanding of the process of fertilisation, in particular their awareness that the egg and the sperm each contribute an equal number of chromosomes to the fertilised egg. There were two questions - 1a asked students to compare chromosome number in the egg cell and the sperm cell; 1b asked students to indicate the number of chromosomes that would be found in the fertilised egg (see Figure 5.1).

Figure 5.1 - part of the '*Reproduction*' probe

If the egg cell contained the chromosomes shown in the diagram above, what chromosomes do you think the sperm cell would contain?

Look at the diagrams below and tick ONE box to show which chromosomes you think would be found in the SPERM CELL.
Please give reasons for your answer.

Tick ONE Box



Please give the reasons for your answer- --

Part 2 was designed to investigate student's understanding of the purpose of sexual reproduction and Part 3 was designed to probe their understanding of reproduction in plants.
All questions had a fixed and a free response section. Students were asked to answer the fixed response question and then to give reasons for their choice (Parts 1 and 3) or an explanation (Part 2).

5.1.3 Critique of the probe

As with 'Cell Division' a fixed response format was selected for the first part of each question in Part 1 because many students found the more open format too difficult. However, in this case the limited options restricted the student's ability to give consistent responses to the two questions. For example, a student who indicated that there were 6 chromosomes in the sperm but was aware that chromosomes combine when egg and sperm fuse would want to tick '9' in response to question 1b - but 9 was not one of the options. The option of 'other response' was needed, but was not included. For this reason tick responses to 1b need to be treated with some caution, with greatest weight being given to the reasoning.

Fewer than one in five of the sample were able to give an explicit response to Part 2. Although it was expected that students might find it difficult to say why sexual reproduction is important it seems likely that the poor wording of Part 2 contributed to this low response rate.

As with 'Cell Division' the range of confused and ambiguous response that were produced made coding difficult but it was possible to pick out a number of ideas with some certainty.

5.1.4 Coding and analysis of the probe

The initial analysis of each question followed the same pattern. The frequency of responses to each option in the fixed response section was noted. The types of reasoning used to justify each option, and the frequency with which each was used were then recorded. Students sometimes used more than one justification, so that totals for any one response may add up to more than 100%. Details of this coding can be found in Appendix 5b.

It might have been revealing to assess consistency of responses across the two questions in Part 1 but this was not possible (see section 5.1.3)

5.2 Analysis of the data

Our sample size for this probe was 478 (99% of those taking part). Overall students responded well to Parts 1 and 3, although they were less confident about the types of reproduction that occurred in plants (Table 5.1). The lower response rate to 1b and the very low response rate to Part 2 may have been a reflection of the problems identified in 5.1.3.

Table 5.1 - breakdown of responses to questions on reproduction

Questions:	Types of Response: didn't know or didn't answer	gave an explicit tick response	gave a reason for their response
Part 1: a) chromosome number in sperm	134 (28% of sample)	344 (72% of sample)	278 (81% of responses)
b)chromosome number in fertilised egg	161 (34% of sample)	317 (66% of sample)	262 (83% of responses)
Part 2: reason for sexual reproduction in animals	345 (72% of sample)	133 (28% of sample)	130 (98% of responses)
Part 3: reproduction in plants	112 (23% of sample)	366 (77% of sample)	284 (78% of responses)

For a breakdown of the exact numbers responding to each part of this probe, and for a more detailed analysis of the student's reasoning, see Appendix 5b.

5.2.1 The process of sexual reproduction

a) comparison of egg and sperm

There were 344 explicit tick responses to the question *'If the egg cell contains 3 chromosomes, how many would be found in the sperm cell?'* of which 81% gave reasons for their response. The data were analysed on the basis of more, less or the same number of chromosomes in egg and sperm (Table 5.2).

Table 5.2 - reasoning related to chromosome number in sperm and egg

chromosome number	main lines of reasoning	number giving this reason	% of those giving this response
more (5 or 6) n = 92; % = 27	• sperm need more chromosomes/genetic information	11	12
	• explicit confusions - terminology (11) - cell and chromosome (6) - fertilisation (4)	21	34
***same (3)** n = 213; % = 62	• recognised the need for equal numbers/matching sets of chromosomes	143	67
	• explicit misunderstandings - sperm acquires chromosomes from the egg (7) - number relates to function of the cell (2)	9	4
	• explicit confusions - cells and chromosomes (3) - sex chromosomes (3)	6	3
less (2) n = 39; % = 11	• sperm needs less chromosomes/genetic information	3	1
	• confusion: sex chromosomes	12	6

** correct response*

Of the 39% of responses which did not recognise that egg and sperm contain the same number of chromosomes, the majority were confused - between cell and chromosomes; about sex chromosomes or by terminology generally:

> *'Because sperm cells have more X-chromosomes'*
> [selected sperm containing 5 chromosomes]
>
> student 8111/16
>
> *'They contain either X or Y chromosomes'*
> [selected sperm containing 2 chromosomes]
>
> student 8113/05
>
> *'Chromosomes keep splitting'*
> [selected sperm containing 6 chromosomes]
>
> student 8112/17
>
> *'Because the chromosomes reproduce themselves before fertilising with the cells'*
> [selected sperm containing 6 chromosomes]
>
> student 3112/22

Of those who explicitly stated that sperm and egg are unequal, the majority believed that sperm needed more chromosomes or genetic information:

> *'It* [sperm] *has the most chromosomes'*
>
> student 9112/02
>
> *'because there is twice as much information in this sperm cell than in the egg cell'*
>
> student 10111/19

Of those who correctly noted that the sperm would have the same number of chromosomes, common confusions and misunderstandings noted elsewhere were still apparent in some of the reasoning, but the majority (67% of this group; 30% of the sample) explicitly recognised the need for matching sets of chromosomes:

> *'They need to match to join together'*
>
> student 8113/13
>
> *'because in the fertilised cell the chromosomes have to match up'*
>
> student 311/27

b) chromosomes number in the fertilised egg

There were 317 explicit tick responses to the question '*How many chromosomes would be found in the fertilised egg?* of which 83% gave reasons for their response (Table 5.3).

The majority of those giving the correct response showed an explicit understanding that chromosomes and/or genetic information from the egg and sperm combine at fertilisation and about one third of these recognised that this resulted in equal numbers (full sets) of chromosomes:

'Because they contain 3 chromosomes from male and 3 from female'

student 8113/16

'The sperm chromosomes and the egg chromosomes combine so that the cell is diploid'

student 3111/02

Table 5.3 - reasoning related to the fertilised egg

chromosome number	main lines of reasoning	number giving this reason	% of those giving this response
*6 n = 202; % = 64	• cells combine • chromosomes/information combines	31 116	15 57
5 n = 39; % = 12	• recognise cells combine but don't recognise need for equal contributions	15	39
3 n = 40; % = 13	• general confusion about the process of fertilisation	14	35
2 n = 36; % = 11	• explicit misunderstandings - parental contribution = 1 (12) - depends on state of the cell (3)	15	42

** correct response*

Of those who recognised that the two cells combined, but who didn't realise that this would result in 6 chromosomes in the fertilised egg, the majority seemed unaware that the egg and sperm made equal inputs:

'I don't know what chromosomes were in the sperm, so I cannot work out this question'

student 9111/23

The number holding this view in response to this question was slightly higher than found in response to question 1a - if the egg cell contains 3 chromosomes, how many will the sperm cell contain?

Of those who thought the number of chromosomes would remain the same, there was widespread confusion but no clear reasoning or common misunderstandings or confusions. However, of those who thought there would only be 2 chromosomes in the fertilised egg the common belief was that each parent contributed only 1 chromosome. This might represent a confusion between cell and chromosome or a belief that each parent contributes just one chromosome - X or Y. Reasoning wasn't always clear but both of these beliefs have been noted in response to a number of other questions:

'It contains X and Y chromosomes'

student 3111/15

'A chromosome from the female and the male cells'

student 3111/24

Confusion between cells and chromosomes was evident across all types of response:

'the cells should all be in pairs and the[re] *must be many to produce an individual'*
[selected sperm containing 6 chromosomes]

student 3111/12

'needs the info + also the sex cell'
[selected sperm containing 5 chromosomes]

student 3112/15

5.2.2 The purposes and benefits of sexual reproduction in animals

Only 133 students thought they had some idea why *'an animal which can reproduce asexually might also need to reproduce sexually'*. While some of these students did not go on to give an explanation, some who said that they had 'no idea', or who gave no tick response, went on to give an explanation. In total 130 went on to give an explanation (see Appendix 5b).

The majority of those giving explanations (44%) suggested that sexual reproduction was important for mixing genes and most showed some understanding of why this might be necessary (in order to increase variation):

'So there will be a variation in the species'

student 8111/16

'The animal reproducing asexually can only produce a clone of itself'

student 8111/20

Almost half of this group (26 students) went on to explain that variation was important for survival, adaptation or evolution:

'these simple creatures also need to have mutation in some reproduction so that the creature could adapt'

student 3111/01

'Because all [each] *new animal* [produced asexually] *would be identical to its parents and so disease would spread quickly'*

student 8112/21

Most of the remainder misunderstood the question or showed confused reasoning.

'they would need to reproduce sexually as well as asexually so that they can feed their babies or so that their babies come out normal i.e. not deformed'

student 8113/17

A small number did not accept that animals needed sexual reproduction.

5.2.3 Sexual reproduction in plants

366 explicitly recognised that reproduction of some kind took place in plants, of which 78% gave reasons for their response (Table 5.4).

Table 5.4 - Reasoning related to reproduction in plants

type of reproduction	main lines of reasoning	number giving this reason	% of those giving this response
sexual only n = 41; % = 11	• recognise a mechanism	17	42
	• confusion: sexual and asexual	3	7
asexual only n = 159; % = 44	• recognise asexual mechanism	4	3
	• don't recognise sexual mechanism	13	8
	• assume movement needed for sexual reproduction	27	17
	• assume external fertilisation cannot be sexual	17	11
	• misunderstand: seeds produced asexually	10	6
	• conflict: recognise sex cells but can't identify a mechanism	14	9
***both** n = 166; % = 45	• purpose (sexual) - variation	9	5
	• purpose (asexual) - rapid propagation	4	2
	• purpose (general) - survival	33	20
	• aware of mechanisms (sexual)	35	22
	• aware of mechanisms (asexual)	8	5
	• misunderstand: seeds produced asexually	5	3
	• misunderstand: plants are sexual *or* asexual	3	2
	• confusion: cross vs self pollination	33	20
	• conflict: sexual reproduction in absence of movement	4	2

* *correct response*

Tick responses were almost equally divided between those who recognised that both types of reproduction occurred in plants and those who thought that only asexual reproduction took place in plants (45% and 44% respectively) with a further 11% believing that only sexual reproduction took place in plants.

Where students failed to recognise that both types of reproduction occur in plants, the most common reason was a failure to recognise a mechanism which might bring sexual reproduction about. In many cases this was due to an incomplete or inaccurate view of the process of sexual reproduction. As a consequence, many students took the inability of plants to move about as evidence that plants could not reproduce sexually:

> *'Plants can't really make sexual contact'*
>
> student 8111/01
>
> *'There is no physical contact between the plants because they can't move'*
>
> student 8113/01

Some students maintained that sexual reproduction was not possible in the absence of movement even though they could identify some of the features of sexual reproduction:

'Well they can't exactly move to have sexual reproduction so they produce both male and female sex cells to produce fruits to produce more of the species'

student 12112/14

Similarly, a number of students were aware that pollination was linked to reproduction but because it was brought about by an external agent they did not recognise it as sexual reproduction:

'because plants are stationary and they use the techniques of pollination'

student 8113/14

A small number recognised seeds to be important in reproduction but took them as evidence of asexual rather than sexual reproduction:

'because the seeds from plants grow when they have left the plants, they do not join with anything else'

student 8112/07

Where both types of reproduction were recognised, students often showed an awareness of the different purposes of reproduction as well as an awareness of the different mechanisms:

'Asexual reproduction is easy, but sexual reproduction means that the offspring have a different genetic code' [confusion between the genetic code and genetic information]

student 8112/21

However, even amongst this group there were several misunderstandings and confusions. Some still believed seeds to be the product of asexual reproduction. Others thought that plants either reproduced sexually or reproduced asexually but not both, and that the plants attractiveness to insects was the deciding factor:

'Because some reproduce by insects or wind carrying pollen onto other plants, as well as asexual taking place in other, less bright plants.

student 12111/29

There was confusion between cross pollination, self pollination and asexual reproduction:

'[sexual reproduction is needed] *to stop inbreeding and inherited diseases coming to light'*

student 12111/19

'..bright coloured plants reproduce sexually because bees bring pollen from other plants to them, where as dark coloured plants make their own pollen (sperm (?) and eggs to fertilise together (HERMAPHRODITE)'

student 12111/30

5.3 Discussion of results

While there was some understanding of the purposes of sexual reproduction (to increase population size; to increase variation) this sample had only a limited understanding of the processes by which these might be achieved.

Many of the difficulties and confusions noted elsewhere, relating to terminology and confusion between cell and chromosome were again apparent.

About one third of the sample recognised that the egg and the sperm make an equal contribution in terms of chromosome number, resulting in matching pairs of chromosomes in the fertilised egg but there was some misunderstanding about the type and role of chromosomes. The belief that chromosomes were all either X or Y and that the only role of chromosomes was to determine sex was not uncommon, although how X and Y might be distributed in a way that resulted in both males and females was unclear.

Of greater difficulty was the recognition that sexual reproduction refers to the fusion of gametes through the process of fertilisation rather that the mechanisms by which the gametes are brought together (copulation in animals, pollination in plants). This confusion had important implications for the student's understanding of reproduction in plants. Many students recognised that pollination was important for reproduction in plants but in the absence of any direct contact between the two plants they did not recognise it as the mechanism by which *sexual* reproduction was brought about. In general, students needed to develop some understanding of the mechanisms and purposes of reproduction (both sexual and asexual) before they were able to accept that sexual reproduction could take place in plants. Even then there were some uncertainties and difficulties. These included:

- the idea that a plant is capable of sexual reproduction or asexual reproduction but not both;
- the relationship between cross fertilisation and self fertilisation and between cross fertilisation and sexual reproduction and self fertilisation and asexual reproduction
- the origin of seeds.

6 The *Information Transfer* probe

6.1 The probe

6.1.1 Design of the probe

This probe (see Appendix 6a) was designed to investigate student's understanding of the transfer of genetic information within an individual. It covers the following conceptual areas (see Appendices 1 and 2):-

A2 - the location of genes

b) location of genes within cells

d) site of mitosis (somatic cells)

A3 - the function of genes

b) genetic information must be copied before it can pass on to new cells during cell division

A4 - mechanisms of gene action

d) mitotic cell division (somatic cells, for growth) results in new cells containing identical numbers of chromosomes and exactly the same genetic information

A5 - similarities and differences between cells

i) within one organism

a) different types of somatic cells all contain the same information

6.1.2 Structure of the probe

This probe was based on just one open format question - *'When the fertilised egg cell divides and grows into a new person, what happens to the genetic information?'*. Some explanation of the origin of that genetic information was presented, in the form of a brief statement and a diagram (see Figure 6.1).

6.1.3 Critique of the probe

This probe was poorly designed for the purpose of providing population data on the student's understanding of the transfer and distribution of genetic information between and within the cells an organism. This was because the open response format allowed this question to be interpreted in a number of different ways and the responses to focus on quite different aspects of the process. For example while some responses focused on the location of genetic information within the organism, others focused the relationship between maternal and paternal input. Difficulty in interpreting student's responses were compounded by the confusions relating to terminology (split, divide, multiply, copy, share etc.) and the confusion between cell and chromosome already noted in Sections 4 and 5.

This probe would have been more effective if it had used a series of more specific questions rather than a single open question.

6.1.4 Coding and analysis of the probe

Because of the difficulties noted in 6.1.3 analysis of the responses to this probe were of necessity superficial. Since students were, in effect, answering a number of alternative questions only limited and cautious conclusions could be drawn at the population level.

In addition many responses - for example *'genetic information is transferred to the new baby'* - added little to the information presented in the question and many others were uncodeable due to the ambiguous use of terminology described in 6.1.3.

Codeable responses were grouped according to the question which the student appeared to be answering. These were:

- Where is genetic information found?
- What happens to the genetic information?
- What is the relationship between maternal and paternal input?

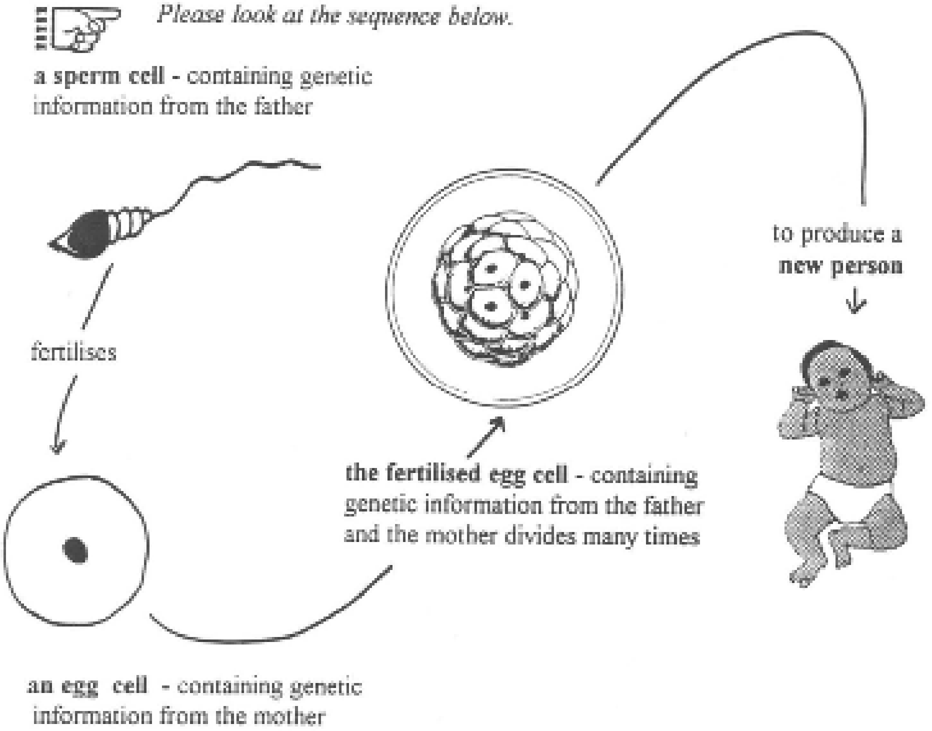
A fourth group - 'additional ideas' - was used to pick up any additional responses.

Within each group the different types of reasoning, and the frequency with which they were used, was noted.

Figure 6.1 - the '*Information Transfer*' probe

When an egg and a sperm join together, genetic information from the father and the mother combine. The fertilised egg, containing this information, divides many times until eventually a new person is formed. This is shown in the sequence below.

Please look at the sequence below.



Please answer the following question.

When the fertilised egg cell divides and grows into a new person, what happens to the genetic information?

....

6.2 Analysis of the data

In total, 432 students responded to this question:
130 [30% of the sample] referred to location of genetic information
259 [60% of the sample] referred to use/transfer of genetic information
70 [16% of the sample] referred to relative maternal and paternal input

6.2.1 Location of genetic information

One third of the responses gave some indication of where genetic information might be found (Table 6.1). Of these the majority indicated some region of the cell. About one quarter were rather vague (*'in the cells'*) but more than one third located genetic information within specific regions of the cell, most frequently the genes. While some students explicitly recognised that genetic information was found in all cells, a few thought that it would only be found in very specific locations such as blood or brain cells.

Table 6.1: Where is genetic information found?

response	number giving this response	% of this group (n = 130)
In cells:	**111**	**85**
a) general		
- cells	29	26
- genes	25	23
- chromosomes	9	7
- cell nucleus	4	3
- DNA	2	2
b) specific		
- all cells	37	28
- blood	3	2
- brain	2	2
In the body of the new person	**20**	**15**

6.2.2 Use or transfer of genetic information

This, the largest group of responses, were closest to the original intention of this probe but almost half of these responses simply indicated that genetic information is transferred, adding little to the information provided in the original question (Table 6.2). About one quarter showed a scientific understanding - that the information is copied into each new cell but more than one in ten stated that genetic information in a cell would change with each division due to the process of splitting, dividing or sharing. A few did not appear to see any link between genetic information and cell division, apparently believing that the genetic information in the fertilised egg is stored somewhere for future use. Many students were unclear as to what happened to the genetic information.

Table 6.2: What happens to the genetic information?

responses	number giving this response	% of this group (n = 259)
all cells receive a copy of (the same) information	62	24
the information is changed - by splitting, dividing, sharing etc.	31	12
unclear whether information remains the same or varies	43	17
information is transferred (similar to the original question; adds little to our understanding of their ideas)	106	41
information is stored (for later use; in sex cells)	12	5

6.2.3 Relative maternal and paternal input

This was the smallest group of responses. Almost half of this group recognised that parents made an equal input (presumably in terms of quantity) but that their input led to new combinations and so to variation. Confusions identified in response to other questions were again evident, with one response showing confusion between gene and chromosome, confusion about sex determination and confusion as to what happens to the genetic information.

Table 6.3 - What is the relationship between maternal and paternal input?

responses (these categories are not mutually exclusive)	number giving this response	% of this group (n = 70)
Parental contribution:		
- Parents make an equal input	31	44
- Parental contributions unequal	1	
Outcome:		
- Inputs mix to give new combinations	34	49
- Inputs give rise to dominant recessive relationships	17	24
- The dominant gene determines the sex of the child, the rest remain in the body	1	

6.2.4 Additional ideas

There were 121 responses in this category. The majority (96; 79% of these responses) recognised that genetic information determines growth and characteristics of the new individual. A few (7) included personality and/or knowledge in this. Roughly one in ten explicitly recognised that there is continuity of genetic information between parent and child.

In addition there seemed to be a sense of genes or genetic information being 'used up' - as when a response indicated that some is used now and some is stored for later.

There also seemed to be a feeling that the new baby somehow makes its own contribution - an idea that the baby has its own DNA or genes in addition to that which it inherits from its parents. Neither of these ideas was quantifiable.

6.3 Discussion of results

It would be unwise to extrapolate from these three groups to the whole sample but these findings appear to support findings from elsewhere in this study. In addition to common misunderstandings and confusions (for example terminology; gene, chromosome and cell) there was evidence of a belief that only some cells or tissues contain genetic information and that genetic information is shared out at cell division. There was also some uncertainty about the extent to which genetic information can determine characteristics.

In addition to the above, two new ideas appeared - the idea that genetic information could be stored in a particular region of the body for future use and the idea that babies generate their own genetic information in addition to that provided by their parents. It was not possible to determine the extent to which ideas occurred in the sample population, nor to gain any clearer understanding of what was meant by them.

7 Discussion

While there was some awareness of the general functions of mitosis (growth and repair) and meiosis (preparation for reproduction) and some awareness of the basic features of fertilisation (egg and sperm combine, resulting in equal 'sets' of chromosomes) there was little indication that students were aware of the processes by which these functions were achieved, or the significance of these processes in terms of the transfer of genetic information.

There was widespread uncertainty as to how genetic information is transferred from cell to cell within an organism. Only a minority of students clearly distinguished between somatic and sperm (or sex) cells and most were unclear as to the distinction between mitotic cell division and meiotic cell division. Given this, it is not surprising that while many students were aware that the newly fertilised egg should have equal amounts, or matching sets, of chromosomes they were unclear as to how this is brought about or why it might be necessary. There was widespread confusion between fertilisation - the process by which genetic information is transferred to the next generation - and the mechanisms which bring fertilisation about. Although there was some recognition that sexual reproduction leads to an increase in genetic variation there was little awareness that this is the main purpose of sexual reproduction and is achieved through the processes of fertilisation - the fusion of genetic information from two different individuals. There was a widespread difficulty in differentiating between the process of fertilisation (the fusion of egg and sperm) and the mechanism which brings this about in animals - copulation.

Inconsistencies in the findings suggested that the knowledge and understandings which the students did have were insecure and influenced by the specific context. In response to the *'Cells'* probe only 4% of the sample correctly distinguished between mitosis and meiosis on basis of genetic information while 59% made no such distinction. In contrast, in response to questioning in *'Cell Division'*, 22 % correctly distinguished on this basis and 38% made no distinction.

Amongst this sample, uncertainty, confusion and a lack of basic knowledge were as common as alternative ideas. Common confusions, evident across a range of questions, included:

- *uncertainty about the relationship between genes and chromosomes;*
- *uncertainty about the relationship between genetic information and chromosomes;*
- *uncertainty about the relationship between chromosomes and cells;*
- *difficulties with the concept of 'cell':-*

  While this study did not set out to investigate young people's understanding of cells, it soon became apparent that a substantial minority of the sample had some problem with the concept. While the extent of this confusion is not easy to quantify, examples of it occurred in response to all probes. The term itself was regularly used interchangeably with 'chromosome' and even 'gene', there was a lack of awareness that all cells have a common basic structure and a lack of awareness that cells are the basic 'building blocks' which make up an organism. Depending on the form of the question, up to 6% of the sample confused cell and chromosome.

- *confusion about the terminology of cell division and its meaning:-*
  Confusion about this was evident, across a number of questions, in up to 6% of the sample. Students seemed to have difficulty with the contradictory terms which are used to describe the processes of cell division in terms of chromosomes and genetic information - divide, replicate, copy, share, split, reproduce and multiply. This confusion was compounded by the students' uncertainty, already noted, about the relationship between cells and chromosomes and would not have been helped by their lack of awareness of the relationship between chromosomes and genetic information.
- *difficulty in distinguishing between processes:-*
  In responding to questions about cell division and fertilisation, up to 5% of the sample seemed to be confused as to which process they were being asked about and responded inappropriately for that particular question.

A small number of alternative understandings could be identified across a range of contexts but individual students did not appear to be consistent in their use of these:

- *cells only contain the genetic information that they need for their specific function*
  This was the most frequently and consistently held alternative understanding.
- *chromosomes and/or genetic information are shared but not copied during cell division*
  This may have been related to the confusions about terminology noted above. Examples of it occurred in response to many questions, with up to 9% of the sample holding this view in relation to chromosomes.
- *all chromosomes are either X or Y*
  Responses to questions relating to cell division and reproduction suggest that up to 4% of the sample believed that all chromosomes are either male (Y) or female (X). Students with this view believed that the distribution of chromosomes during meiosis or fertilisation was related to their sex and depended on the type of sex cell (egg or sperm) being produced or the sex of the newly fertilised egg (male or female).
- *chromosome number is related to age or health of a cell*
  This view was expressed in up to 2% of responses to some questions.

Given the size and structure of the sample there is no reason to suppose that these findings would be atypical for the larger population from which this sample was drawn. As a consequence these findings have important implications for teaching and for curriculum design. These findings, together with the limited understanding of basic structures and concepts identified in Working Paper 2 (Lewis *et al*, 1997b), make it difficult to see how these students might understand the interpretation of genetic information within an organism, resulting in the development of specific characteristics; the inheritance of characteristics across generations or the basic principles of genetic engineering. There seems little point in attempting to teach some of these more complex genetic concepts without ensuring that students have some understanding of the basic ideas on which they are based. This might require explicit provision of coherent conceptual frameworks in which to place the ideas. In the absence of these it is difficult for students to make any sense of isolated 'facts' especially when some of the basic ideas presented within these 'facts' are counter-intuitive.

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Appendix 1- List of Concepts Related to A Basic Understanding of Genetics and DNA Technology

A) Basic Genetics

1. Language

a) terms related to basic genetics (knowledge of terminology)
b) range of organisms

2. Location

a) location of genes within organisms (relationship between structures)
b) location of genes within cells
c) relationship between structures, from gene to whole organism
d) site of mitosis (somatic cells)
e) site of meiosis (germ cells)

3. Function of Genes

a) genes code for proteins (expression/replication)
b) genetic information must be copied to pass on to new cells during cell division

4. Mechanism of Gene Action

a) a single gene may exist in different (switches/codes/variation) forms (alleles) which may produce different phenotypes; this results in variation
b) gene expression depends on environment (internal and external) to 'trigger' switches
c) the 'code' is universal - the same in all organisms
d) mitotic cell division (somatic cells, for growth) results in new cells containing identical numbers of chromosomes and exactly the same genetic information
e) meiotic cell division (germ cells, for reproduction) results in new cells containing half the chromosome number and different genetic information (increases variation)
f) fertilisation gives continuity, (genetic information passes from parents to child), and variation (mixing of alleles)

5. Similarities/Differences Between Cells

i) within one organism
a) different types of somatic cells all contain the same information
b) different cell structure/function (somatic cells) achieved by differential activation of genes (notion of gene 'switches') - see 4b
c) germ cells contain different genetic information even though they are the same type of cell (see 4e)

ii) between organisms/within species

a) production of germ cells results in variation (see 4e/5a) ; random combination of germ cells at fertilisation leads to even greater variation; result is that cells from different organisms always contain different genetic information (exception = monozygous twins - they arise from same fertilised egg)

b) alleles are source of variation

c) selective pressures will alter the frequency of different variations within the gene pool (i.e. alter the frequency of different alleles)

iii) between different species

a) all organisms contain genetic (prokaryotic vs. eukaryotic; information plant vs. animal)

b) the genetic information is always coded in the form of nucleic acids

c) the code is understood or 'read' (translated) in the same way in all organisms

d) genetic information is copied and passed on during cell division in all organisms

B) DNA Technology

1. Techniques

a) terms used to describe techniques

b) understanding of the terms

2. Applications

a) real or potential

Appendix 2 - Conceptual Areas Covered By The Written Probes

a) Probes reported in Working Paper 2

Area	*'Size Sequence'*	*'Living Things'*	*'Biological Terms'*	*'The New Genetics'*
A1a	●		●	
A1b		●		
A2a	●			
A2b	●		●	
A2c	●	●	●	
A2d				
A2e				
A3a			●	●
A3b			●	
A4a			●	
A4b				
A4c				●
A4d				
A4e				
A4f				
A5ia				
A5ib				
A5ic				
A5iia				
A5iib				
A5iic				
A5iiia		●		
A5iiib				●
A5iiic				●
A5iiid				
B1a				●
B1b				●
B2a				

b) Probes reported in this Working Paper

Area	*'Cells'*	*'Cell Division'*	*'Reproduction'*	*'Information Transfer'*
A1a				
A1b				
A2a				●
A2b				●
A2c				
A2d		●		●
A2e		●		
A3a				
A3b		●		●
A4a				
A4b	●			
A4c				
A4d	●	●		●
A4e	●	●		
A4f			●	
A5ia	●			●
A5ib	●			
A5ic	●		●	
A5iia	●		●	
A5iib	●			
A5iic				
A5iiia				
A5iiib				
A5iiic				
A5iiid		●		
B1a				
B1b				
B2a				

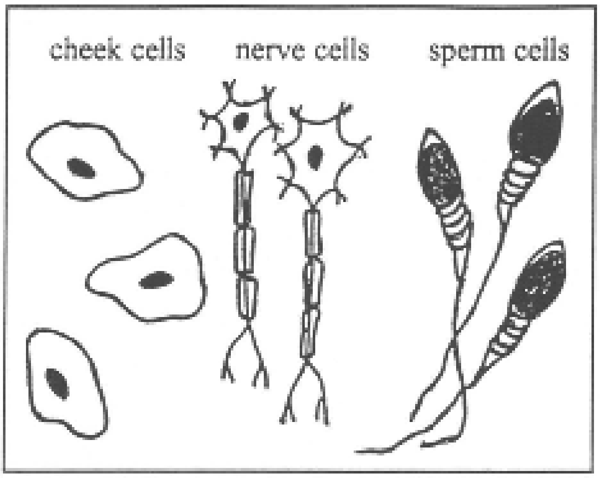
Appendix 3a: Cells

'Cells'

Part 1

This part of the question is about different types of cells from the same person - Robert.

Cells from Robert



Please answer the following questions by ticking ONE box.
Explain your reasons.

a) If you could take two of Robert's cheek cells would the genetic information in them be :-

Tick ONE Box

the same ☐

different ☐

don't know ☐

Please give the reasons for your answer - --

Appendix 3a: Cells continued

b) If you could take one of Robert's cheek cells and one of Robert's nerve cells would the genetic information in them be :-

Tick ONE Box

the same ☐

different ☐

don't know ☐

Please give the reasons for your answer - ---------------------------------------

----

----

c) If you could take one of Robert's cheek cells and one of Robert's sperm cells would the genetic information in them be :-

Tick ONE Box

the same ☐

different ☐

don't know ☐

Please give the reasons for your answer - ---------------------------------------

----

----

d) If you could take two of Robert's sperm cells would the genetic information in them be :-

Tick ONE Box

the same ☐

different ☐

don't know ☐

Please give the reasons for your answer - ---------------------------------------

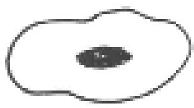
----

Appendix 3a: Cells continued

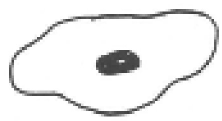
Part 2

This part of the question asks you to make comparisons between the cells from two different people - Danny and John.

a) Danny's cheek cell



John's cheek cell



If you could take one of Danny's cheek cells and one of John's cheek cells would the genetic information in them be :-

	Tick ONE Box
the same	☐
different	☐
don't know	☐

Reasons --

Appendix 3b: Cells - frequency of responses

Analysis Of Responses

The main responses to each question are set out part by part in the following pages. Ambiguous or incomprehensible responses are not included. Nor are views expressed by very few (one or two) individuals - unless grouped under 'other responses'. Occasionally the coding is not exclusive (more than one of the listed views may have been expressed by one person) therefore the total may add up to more than 100% at times.

Number of responses

sample size (number responding to some part of this probe) = 478

numbers attempting Part 1 = 478 [100% of the sample]
numbers attempting Part 2 = 475 [99.4% of the sample]

Part 1: cells from the same person

Ticked responses

	Genetic information in the two cells would be.......		
comparison:	same	different	don't know
2 cheek cells	330* [69.0%]	76 [15.9%]	70 [14.6%]
1 cheek cell, 1 nerve cell	78* [16.3%]	320 [66.9%]	80 [16.7%]
1 cheek cell, I sperm cell	63 [13.2%]	323* [67.6%]	92 [19.2%]
2 sperm cells	237 [49.6%]	159* [33.3%]	79 [16.5%]

* *correct answer*
[x %] indicates % of total responses to Part 1

Reasoning

This was coded under three headings:

(i) reasons relating to somatic cells (Parts 1a and 1b combined)
n = 401; 83.9% of responses to Part 1

(ii) reasons relating to sperm cells (Parts 1d)
n = 312; 65.3% of responses to Part 1

(iii) reasons reflecting the relationship between somatic and sperm cells (Parts 1c)
n = 335; 70.1% of responses to Part 1

Appendix 3b: Cells Part 1, reasons relating to somatic cells

(i) reasons relating to somatic cells	number giving this response	% of those giving reasons (401)	% responding to this probe (478)
consistent reasoning	**273**	**68.1**	**57.1**
both types of cell have the same genetic information	**64**	**16.0**	**13.4**
-all cells from one individual contain the same information	57	14.2	11.9
[relate this to cell division]	[10]	[2.5]	[2.1]
[recognise differential gene expression]	[2]	[<1.0]	[<1.0]
cells of the *same type* have the same genetic information	**169**	**42.1**	**35.4**
- cells with different structure or function need different information	163	40.6	34.1
***all* cells have different genetic information**	**40**	**10.0**	**8.4**
- *all* cells have slightly different structure, function, size or shape and so have different information	33	8.2	6.9
confused or contradictory reasoning	**110**	**27.4**	**23.0**
conflict (learnt vs intuitive?): all cells have the same information but cells of different types need different information	**32**	**8.0**	**6.7**
uncertain: cells of different types need different information; not sure about cells of the same type	**35**	**8.7**	**7.3**
uncertain: cells of the same type have the same information; not sure about cells of a different type	**14**	**3.5**	**7.1**

Appendix 3b: Cells Part 1, reasons relating to sperm cells

(ii) reasons relating to sperm cells	number giving this response	% of those giving reasons (312)	% responding to this probe (478)
All sperm contain the same genetic information	**173**	**55.4**	**36.2**
don't appear to distinguish between somatic and sperm cells	**126**	**39.4**	**26.4**
- all cells (from one individual) contain the same genetic information	27	8.7	5.6
- cells of the same type contain the same genetic information	99	31.7	20.7
don't appear to distinguish between genes and genetic information:	**33**	**10.6**	**6.9**
all sperm need the same information to pass on to the next generation [each sperm needs copy of each of Robert's genes]	[25]	[8.0]	[5.2]
Different sperm contain different genetic information	**141**	**45.2**	**29.5**
offspring show variation	**37**	**11.9**	**7.7**
recognition of meiosis (various levels)	**12**	**3.8**	**2.5**
genes are mixed up (no indication of purpose or process)	**15**	**4.8**	**3.1**
differences relate to X and Y chromosomes	**39**	**12.5**	**8.2**
don't appear to distinguish between somatic and sperm cells: all cells contain different genetic information	**11**	**3.5**	**2.3**

Appendix 3b: Cells Part 1, reasons relating to somatic and sperm cells

(iii) reasons relating to the relationship between somatic and sperm cells	number giving this response	% of those giving reasons (335)	% responding to this probe (478)
the genetic information is different	**272**	**81.2**	**56.9**
don't appear to distinguish between somatic and sperm cells	**198**	**59.1**	**41.4**
- cells of the same type contain the same genetic information	193	57.6	40.1
- all cells contain different genetic information	5	1.3	1.0
difference is due to XY chromosomes	**4**	**1.2**	**<1.0**
difference relates to production or function of sperm	**26**	**7.8**	**5.4**
- refer to variation in offspring	21	6.3	4.4
- refer to meiosis and outcomes	5	1.3	1.0
sperm contain half the genes, genetic information, chromosome number	**26**	**7.8**	**5.4**
sperm contain more information	**14**	**4.2**	**2.9**
- no justification	5	1.3	1.0
- sperm must contain full set of information drawn form all the different types of cell	9	2.7	1.9
the genetic information is the same	**45**	**13.4**	**9.4**
don't appear to distinguish between somatic and sperm cells all cells (from one individual) contain the same genetic information	**32**	**9.6**	**6.7**
don't appear to recognise the processes of meiosis and fertilisation sperm need the same information as the cheek cell to pass on to offspring	**10**	**3.0**	**2.1**
confused or conflicting reasoning	**18**	**5.4**	**3.8**

Appendix 3b: Cells Part 2, comparison betweeen individuals

Part 2: cheek cells from two different people (n = 475)

Tick responses response	number giving this response	% responding to this question (n = 475)	% responding to this probe (n = 478)
genetic information is the same	10	2.1	2.1
genetic information is different	407	85.7	85.7
don't know	57	12.0	12.0
no response	4	<1.0	<1.0

* *correct response*

Reasoning
(n = 385: 81.1% of those responding to this question)

a) reasons why genetic information is the same (n = 10)	number giving this response	% of those giving reasons (385)	% responding to this probe (478)
the two cells have the same structure/function	5	1.3	1.0
unclear reasoning	2		
no reason	3		

b) reasons why genetic information is different (n = 407)	number giving this response	% of this group (407)	% of those giving reasons (385)	% responding to this probe (478)
different people have different genetic information (no explanation of this)	249	61.2	64.7	52.4
as above; reason relates to differences in parents, sperm, nucleus	71	17.4	18.4	14.9
as above; reasons relate to DNA	19	4.7	4.9	4.0
relate difference to gene expression - different physical appearance of cheek*	19	4.7	4.9	4.0
distinguish between genes (similar for both) and genetic information (different for both)	7	1.7	1.8	1.5
try to resolve conflict with answer to Part 1 - cells *slightly* different re physical appearance or function	7	1.7	1.8	1.5
other	9	2.2	2.3	1.9
no reasons	26	6.4	6.8	5.5

* *this type of response may reflect some understanding of gene expression (recognising difference gene and genetic information)but might be attempt to resolve conflict with Part 1 - cells same type.*

Appendix 3c: Cells - understanding of the science

Analysis was based on the combination of ticked responses, using students' reasoning to support the interpretation.

(i) only responding to some of the 4 parts

number = 188 [39.3% of responses; 39.0% of the sample]

	number giving this response	% of this group (188)	% responding to this probe (478)
no discernible reasoning	41	21.8	8.6
expressed a range of ideas but uncertain/inconsistent (reflected in failure to complete all parts)	147	78.2	30.8

(ii) responding to all 4 parts

number = 290 [60.7% of responses; 60.2% of the sample]

	number giving this response	% of these responses (290)	% responding to this probe (478)
do not **distinguish between sperm and somatic cells**	**171**	**60.0**	**35.8**
- *all* cells contain the same genetic information	28	9.7	5.9
- *all* cells contain different genetic information	28	9.7	5.9
- cells of the *same type* contain the same genetic information	115	39.7	24.1
do **distinguish between sperm and somatic cells**	**79**	**27.2**	**16.5**
- all *somatic* cells contain the same information; sperm cells are different from somatic cells but the same as each other	8	2.8	1.8
- all somatic cells are different but sperm cells all contain the same genetic information	14	4.8	2.9
- cells of the same type have the same genetic information except for sperm cells - each of these has different genetic information	57	19.7	11.9
correctly distinguish between somatic and sperm cells [somatic cells all contain the same genetic information; sperm cells are different to somatic cells and to each other]	**20**	**6.9**	**4.2**
contradictory reasoning	**20**	**6.9**	**4.2**

Appendix 3c: Cells - understanding the science

	1. *biological reasoning?*	2 - *different jobs need different information?*	3 - *sharing out fertilised egg?*
No differentiation between somatic and sperm cells	1.1 All cells contain the same genetic information	2.1 Cells of the same type have the same genetic information; each type of cell has different genetic information.	3.1 All cells are genetically different
Differentiation between somatic & sperm cells	1.2 All somatic cells are genetically identical; all sperm cells are genetically identical; sperm cells are genetically different to somatic cells.	2.2 Each type of cell is genetically different to each other type of cell; sperm cells are also genetically different to each other	3.2 All somatic cells are genetically different; sperm cells are genetically different to somatic cells but the same as each other
Scientific understanding	1.3 All somatic cells contain the same genetic information; somatic cells are genetically different to sperm cells; sperm cells are genetically different to each other.		

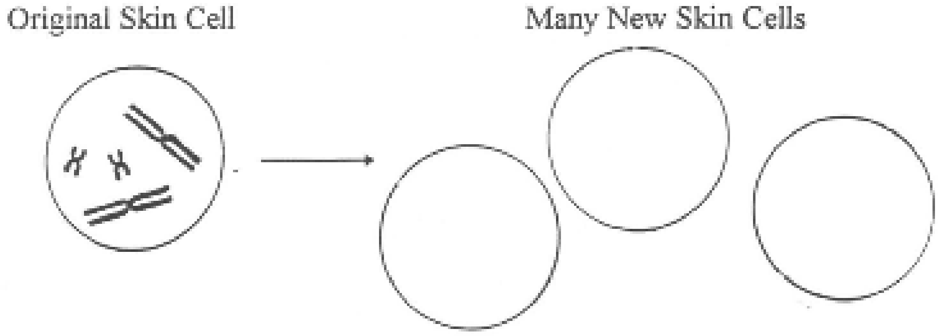
Appendix 4a: Cell Division

'Cell Division'

This question is in two parts.
Part 1 asks about cell division for growth and repair.
Part 2 asks about cell division for the production of sex cells.

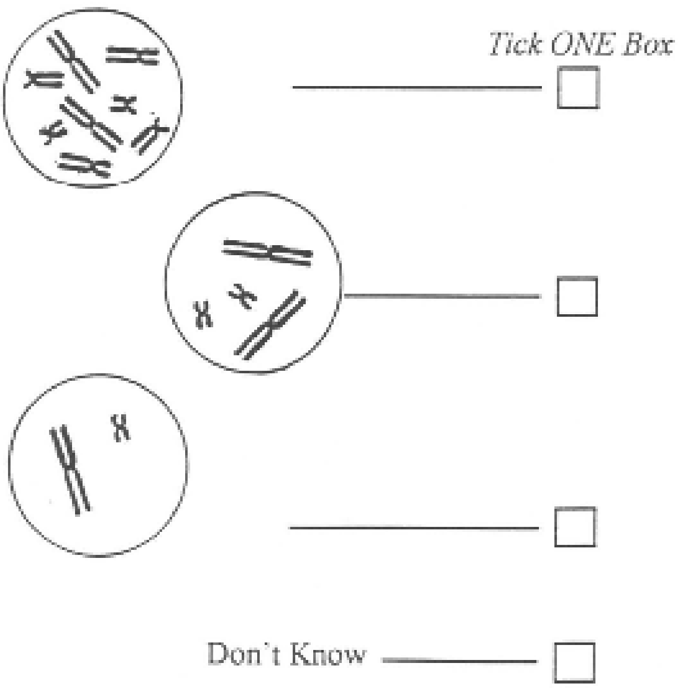
Part 1

In animals, skin cells divide again and again to produce many new skin cells.
In the diagram below some chromosomes have been drawn into the original cell.



If the original skin cell contained the chromosomes shown in the diagram above, what chromosomes do you think the new skin cells would contain?

Look at the diagrams below and tick ONE box to show which chromosomes you think would be found in the NEW SKIN CELLS.
Please give reasons for your answer.



Reason- ---

Appendix 4a: Cell Division continued

Would the new skin cells and the original skin cell contain the same or different genetic information?

Please tick ONE box, then give your reasons.

Tick ONE box

the same ☐

different ☐

don't know ☐

Reasons - --

For each part of the body listed below please tick ONE box to show whether or not you think the cells in that part of the body would divide in this way.

	yes	no	don't know
muscle	☐	☐	☐
testis	☐	☐	☐
ovary	☐	☐	☐
kidney	☐	☐	☐
stomach	☐	☐	☐

The questions so far have all been about animal cells.

Do you think that this type of cell division for growth also occurs, in the same way, in plants?

Please tick ONE box, then give your reasons.

Tick ONE Box

yes ☐

no ☐

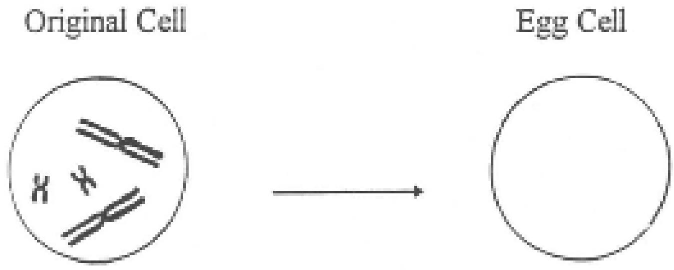
Reasons --

Appendix 4a: Cell Division continued

Part 2

Cells also divide when sex cells (eggs and sperm) are being produced.

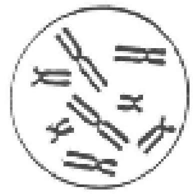
In the diagram below some chromosomes have been drawn into the original cell.



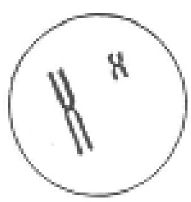
If the original cell contained the chromosomes shown in the diagram above, what chromosomes do you think the egg cell would contain?

Look at the diagrams below and tick ONE box to show which chromosomes you think would be found in the EGG CELL.
Please give reasons for your answer.

Tick ONE Box

 ———— ☐

 ———— ☐

 ———— ☐

Don't Know ———— ☐

Reasons- --

Appendix 4a: Cell Division continued

Would the new egg cell and the original cell contain the same or different genetic information?

Please tick ONE box, then give reasons for your answer.

Tick ONE box

the same ☐

different ☐

don't know ☐

Reasons - --

For each part of the body listed below please tick ONE box to show whether or not you think the cells in that part of the body would divide in this way.

	yes	no	don't know
muscle	☐	☐	☐
testis	☐	☐	☐
ovary	☐	☐	☐
kidney	☐	☐	☐
stomach	☐	☐	☐
skin	☐	☐	☐

So far, the questions in Part 2 have all been about animal cells.

Do you think that this type of cell division, for production of sex cells, also occurs in plants?

Please tick ONE box, then give reasons for your answer.

Tick ONE Box

yes ☐

no ☐

Reasons --

Appendix 4b: Cell Division - frequency of responses

Analysis Of Responses

The main responses to each question are set out part by part in the following pages. Ambiguous or incomprehensible responses are not included. Nor are views expressed by very few (one or two) individuals - unless grouped under 'other responses'. Occasionally the coding is not exclusive (more than one of the listed views may have been expressed by one person) therefore the total may add up to more than 100% at times.

Number of responses

sample size (number responding to some part of this probe) = 481

numbers attempting Part 1(mitosis)	= 481	[100% of the sample]
a) chromosome number	= 478	[99.4% of the sample]
b) genetic information	= 477	[99.2% of the sample]
c) location	= 480	[99.8% of the sample]
d) in plants	= 453	[94.2% of the sample]

numbers attempting Part 2 (meiosis)	= 481	[100% of the sample]
a) chromosome number	= 479	[99.6% of the sample]
b) genetic information	= 472	[98.1% of the sample]
c) location	= 463	[96.3% of the sample]
d) in plants	= 424	[88.1% of the sample]

This appendix is in several sections:-

Part 1: mitotic cell division
1a - chromosome number in resultry cells
1b - genetic information in resulting cells
1c - location of mitosis
1d - mitosis in plants

Part 2: meiotic cell division
2a - chromosome number in resulting cells
2b - genetic information in resulting cells
2c - location of meiosis
2d - meiosis of plants

Appendix 4b: Cell Division, mitosis/chromosome number

Part 1: Mitotic cell division
1a) chromosomes number:
'How many chromosomes would a new skin cell have compared with the original skin cell?'

Tick responses (n = 478)

number of chromosomes	number giving this response	% responding to this question (n = 478)	% responding to this probe (n = 481)
4 (the same)*	220	46.0	45.7
8 (double)	101	21.1	21.0
2 (half)	80	16.7	16.6
don't know	77	16.1	16.0
[ticked don't know]	[75]		
[multiple ticks]	[2]		

* *correct response*

Reasoning (n = 362: 76% of those responding to this question)

Reasons	Number giving this reason	% of those giving this response	% of those giving reasons (n = 362)
the same number (n = 220)			
*compatible with the science i.e. chromosomes copied/shared	93	42.3	25.7
[generalise (*all* cells; no distinction somatic and germ)]	[17]	[7.7]	[4.7]
*cells of same type/function	80	36.4	22.1
*gave no reason	13	5.9	-
double the number (n = 101)			
*confusion:			
- process and structure - splitting, copying; cell or chromosome	26	25.7	7.2
- between cell and chromosome	26	25.7	7.2
*misunderstanding			
- chromosome number depends on the state of the cell (age or health)	11	10.9	3.0
* no reason	16	15.8	-
half the number (n = 80)			
*chromosomes shared but not replicated	43	53.8	11.9
*no reason	13	16.2	-

Appendix 4b: Cell Division, mitosis/genetic information

1b) genetic information:
'Would the new skin cell and the original skin cell have the same or different information?'

Tick response: (n =477)

nature of genetic information	number giving this response	% responding to this question (n = 477)	% responding to this probe (n = 481)
the same	312	65.4	64.9
different	65	13.6	13.5
don't know	100	21.0	20.8

Reasoning (n =328: 69% of those responding to this question)

reasons	Number giving this reason	% of those giving this response	% of those giving reasons (n = 328)
the same information (n = 312)			
*the cells are the same type	51	16.3	15.5
**all* cells contain same information (no distinction somatic and germ cells)	43	13.9	13.1
*information *within body* unchangeable	22	7.1	6.7
[even if C. number within cell changes]	[4]	[1.3]	1.2
*copied from parent/original cell (may include some implicit 'cells of same type')	110	35.3	33.5
*no reason	33	10.6	-
b. different information (n = 65)			
*depends on the state of the cell (age or health)	9	13.8	2.7
*small numbers and unrelated ideas (note 1)	11	-	-
*small numbers and confusions (note 2)	6	-	-
* no reason	18	27.7	-

note 1
No other commonly held ideas were apparent. Instead, a number of unrelated ideas were revealed:
- 4 thought that genetic information would relate to the appearance of the cell/part of body
- perhaps linked to this, 1 thought the genetic information would depend on the location of the cell
- 3 said that the information would be different because the C number would be different
- 2 thought that genetic information was shared out at cell division
- 1 said that copying was not exact

note 2
A number of confusions were also apparent:
- about the type of cell division, with references to sperm and egg (2)
- between genetic code and genetic information (1)
- about splitting, dividing, multiplying in relation to C's and cells (3)

Appendix 4b: Cell Division, mitosis/location; in plants

1c) location of mitotic cell division: what combination of tissues do they tick?
Summary of tick responses (n = 480)

location	number giving this response	% responding to this question (480)
somatic tissues only*	140	29.2
gonads only	102	21.3
mixture of both	163	34.0
don't know	76	15.8

* *correct answer*

1d) plants:
'Does this type of cell division also occur, in the same way, in plants?'
Tick response (n = 453)

response	number giving this response	% responding to this question (n = 453)	% responding to this probe (n = 481)
yes	299	66.0	62.2
no	147	32.5	30.6
don't know	35	-	7.3
[ticked don't know]	[7]	[1.5]	[1.5]
[didn't respond]	[28]	-	[5.8]

Reasoning (n = 330: 73% of those responding to this question)

reasons	Number giving this reason	% of those giving this response	% of those giving reasons (n = 330)	% responding to this probe (n = 481)
a) yes, plant cells divide by mitosis (n = 299)				
*plants are living, like animals (needed for growth, repair etc.)	157	52.5	47.6	32.6
*confusions				
- relating to sex cells/reproduction	13	4.3	3.9	2.7
* misunderstandings				
- there is no other type of cell division in plants	6	2.0	1.8	1.2
* no reason	78	26.1	-	-
b) no, plants do not divide by mitosis (n = 147)				
*plant are not like animals (2 are explicit: plant cells do not divide)	64	43.5	19.4	13.3
*confusion				
- about type of cell division?	11	7.5	3.3	2.3
*misunderstanding				
- plants are *not living*	2	1.4	<1.0	<1.0
* no reason	57	38.8	-	-

Appendix 4b: Cell Division, meiosis/chromosome number

Part 2: Meiotic cell division

2a) chromosomes number:
'How many chromosomes would the egg cell contain, compared with the original cell?'
Tick response (n = 479)

number of chromosomes	number giving this response	% responding to this question (479)	% responding to this probe (481)
4 (the same)	110	23.0	22.9
8 (double)	72	15.0	15.0
c: 2 (half)*	148	30.9	30.8
don't know [ticked don't know] [multiple ticks]	149 [144] [5]	31.2	31.0

* *the correct response*

Reasoning (n = 277: 58% of those responding to this question)

reasons	Number giving this reason	% of those giving this response	% of those giving reasons (n = 277)
the same number (n = 110)			
• don't appear to distinguish between somatic and germ cells	63	57.3	22.7
• appeared to be confused with fertilisation	3	2.7	1.1
• gave no reason	19	17.3	-
double the number (n = 72)			
*confusion:			
- process and structure: splitting, copying; cell or chromosome	13	18.1	4.7
- appeared to be confused with fertilisation	7	9.7	2.5
*misunderstanding	10	13.9	3.6
- sex cells should contain *more* chromosomes	2	2.7	<1.0
- chromosome number depends on the state of the cell (age or health)	21	29.2	-
* no reason			
half the number (n = 144)			
*chromosomes are split/shared equally	69	47.9	24.9
[i)explicitly recognise need for reduction division before fertilisation]	[40]	[27.8]	[14.4]
[ii)general - may relate to view of cell division as sharing but not copying chromosomes]	[29]	[20.1]	[10.5]
*confusion			
- about sex chromosomes	9	6.3	3.2
*no reason	17	11.8	-

Appendix 4b: Cell Division, meiosis/genetic information

2b) genetic information:
'Would the egg cell and the original cell have the same or different information?'

Tick response (n = 472)

nature of genetic information	number giving this response	% responding to this question (472)	% responding to this probe (481)
the same	178	37.7	37.0
different*	163	34.5	33.9
don't know	131	27.8	27.2

* *the correct response*

Reasoning (n = 263: 56% of those responding to this question)

reasons	Number giving this reason	% of those giving this response	% of those giving reasons (n = 263)	% of those answering this probe (481)
the same information (n = 178)				
*new cell is a copy of original	60	33.7	22.3	12.5
*relate genetic information. to function	18	10.1	6.8	3.7
*egg contains *all* information needed for next generation	9	5.1	3.4	1.9
*genetic information cannot be changed	7	3.9	2.7	1.5
* no reason	36	20.2	-	7.5
different information (n = 163)				
*linked genetic information and variation in offspring	74	45.4	28.1	15.4
[(i) explicitly mention processes which bring this about]	[35]	[21.5]	[13.3]	[7.3]
*confusion with fertilisation?	13	8.0	4.9	2.7
*relate genetic information. to function (no distinction meiosis and mitosis)	6	3.7	2.3	1.2
* no reason	43	26.4	-	8.9

Appendix 4b: Cell Division, meiosis/location; in plants

2c) location of meiotic cell division: what combination of tissues do they tick?

Summary of tick responses (n = 463)

location	number giving this response	% responding to this question (463)	% responding to this probe (481)
somatic tissues only	71	15.3	14.8
gonads only*	119	25.7	24.7
mixture of both	180	38.9	37.4
don't know	108	23.3	22.5

* *correct answer*

2d) plants:
'Does this type of cell division, for the production of sex cells, also occur in plants?'

Tick response (n = 424)

response	number giving this response	% responding to this question (424)	% responding to this probe (481)
a) yes	212	50.0	44.1
b) no	204	48.1	42.4
c) don't know	65	-	13.5
[ticked don't know]	8	1.9	
[didn't respond]	57	-	

Reasoning (n = 277: 65% of those responding to this question)

reasons	Number giving this reason	% of those giving this response	% of those giving reasons (n = 277)	% of those answering this probe (n = 481)
yes, plant cells divide by meiosis (n = 212)				
*plants are living, like animals	100	47.2	36.1	20.8
- *!caution, may not all be distinguishing the two types of division*	[70]	[33.0]	[25.3]	[14.6]
[explicitly mention sex cells/reproduction]	15	7.1	5.4	3.1
*confusions relating to type of cell division?	70	33.0	-	-
* no reason				
no, plants do not divide by meiosis (n = 204)				
*plant are not like animals	97	47.4	35.0	20.2
[i) sex is different in plants]	[27]	[13.2]	[9.7]	[5.6]
[ii) explicit: there is no sex in plants]	[31]	[15.2]	[11.2]	[6.4]
[iii) implicit: no sex in plants]	[8]	[3.9]	[2.9]	[1.7]
*confusion about type of cell division?	9	4.4	3.2	1.9
* no reason	86	42.2	-	-

Appendix 4c: Cell Division, comparison of mitosis and meiosis

For the purposes of the following analyses those ticking 'don't know', ticking more than one option or not responding to the question have been grouped together as 'don't know'

a) comparison on the basis of chromosome number

	chromosome number: meiosis			
chromosome number: mitosis	8	4	2	don't know
8	30	18	17	36
4	22	73	86	39
2	11	10	37	22
don't know	9	9	8	55

b) comparison on the basis of genetic information

	genetic information: meiosis		
genetic information: mitosis	same	different	don't know
same	145	106	61
different	11	40	14
don't know	22	17	66

c) comparison on the basis of location.

See following page.

d) comparison on the basis of response to plants

	Does meiosis occur in plants?		
Does mitosis occur in plants?	yes	no	don't know
yes	165	107	27
no	40	88	19
don't know	7	9	20

Appendix 4c: Cell Division, comparison of mitosis and meiosis

c) comparison on the basis of location

cross tabs: location of mitosis x location of meiosis

		meiosis				
		1	**2**	**3**	**4**	**5**
mitosis	**1:** ticked *all* options	7	0	1	3	4
	2: ticked somatic cell options only	2	25	67	23	23
	3: ticked germ cell options only	0	12	26	53	11
	4: ticked a combination of both	1	20	18	82	27
	5: other responses	0	14	7	9	46

From this the following can be identified. Those who:

(i) ***do distinguishing between meiosis and mitosis on the basis of location***

67 correctly located mitosis in somatic tissues *and* meiosis in gonads [meiosis = 3; mitosis = 2]

48 correctly located mitosis but not meiosis (see also 'distinguishing between somatic and germ cells', below)[meiosis **not** = 3; mitosis = 2]

26 correctly located meiosis but not mitosis (see also 'distinguishing between somatic and germ cells', below)[meiosis = 3; mitosis **not** = 2]

12 showed reversal: located mitosis in gonads and meiosis in somatic tissues [meiosis = 2; mitosis = 3]

(ii) ***not distinguishing between meiosis and mitosis on the basis of location***

89 indicated that cell division (either type) can take place in either type of cell [meiosis = 1 or 4; mitosis = 1 or 4]

(iii) ***distinguishing between somatic and germ cells, but not necessarily between mitosis and meiosis***

25 indicated that cell division (any type) only takes place in somatic cells (overlaps [meiosis = 2; mitosis = 2]

26 indicated that cell division (any type) only takes place in germ cells [meiosis = 3; mitosis = 3]

(iv) ***other responses (including 'don't know')***

183 confused, uncertain or didn't know

The findings above are summarised in this table	number giving this response	% responding to this probe (n = 481)
distinguishing between meiosis and mitosis on the basis of location	**153**	**31.8**
- correctly located mitosis in somatic tissues *and* meiosis in gonads	67	13.9
- correctly located mitosis but not meiosis	48	10.0
- correctly located meiosis but not mitosis	26	5.4
- reversal: located mitosis in gonads and meiosis in somatic tissues	12	2.5
not distinguishing between meiosis and mitosis on the basis of location	**89**	**18.5**
distinguishing between somatic and germ cells, but not necessarily between mitosis and meiosis	**51**	**10.6**
- all cell division occurs in somatic tissues	[25]	[5.2]
- all cell division occurs in gonads	[26]	[5.4]
other responses (including 'don't know')	**183**	**38.0**

Appendix 5a: Reproduction

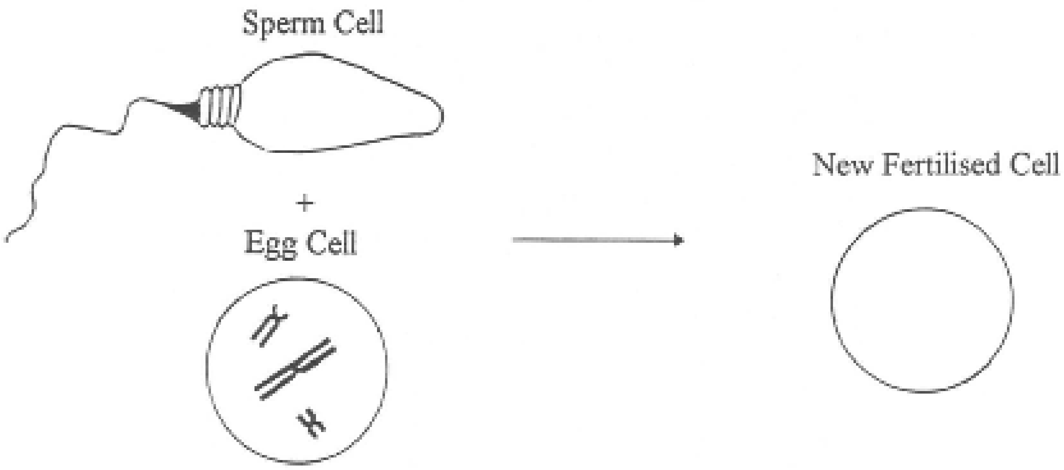
'Reproduction'

This question is in three parts.

Part 1

In animals, when a sperm cell fertilises an egg cell a new cell is formed. This is the process of sexual reproduction. This new cell then develops into a new animal.

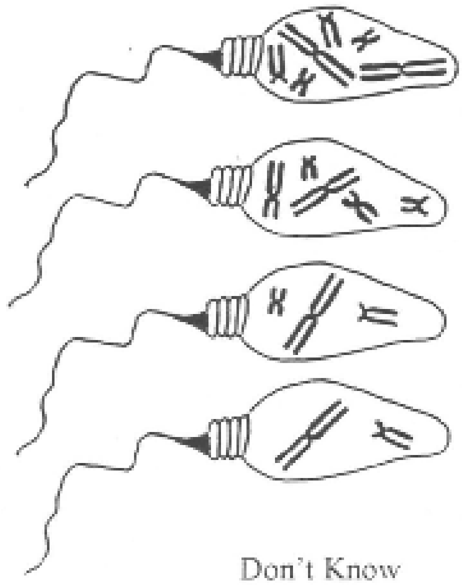
In the diagram below some chromosomes have been drawn into the egg cell.



If the egg cell contained the chromosomes shown in the diagram above, what chromosomes do you think the sperm cell would contain?

Look at the diagrams below and tick ONE box to show which chromosomes you think would be found in the SPERM CELL.
Please give reasons for your answer.

Tick ONE Box



- ______________________ ☐
- ______________________ ☐
- ______________________ ☐
- ______________________ ☐

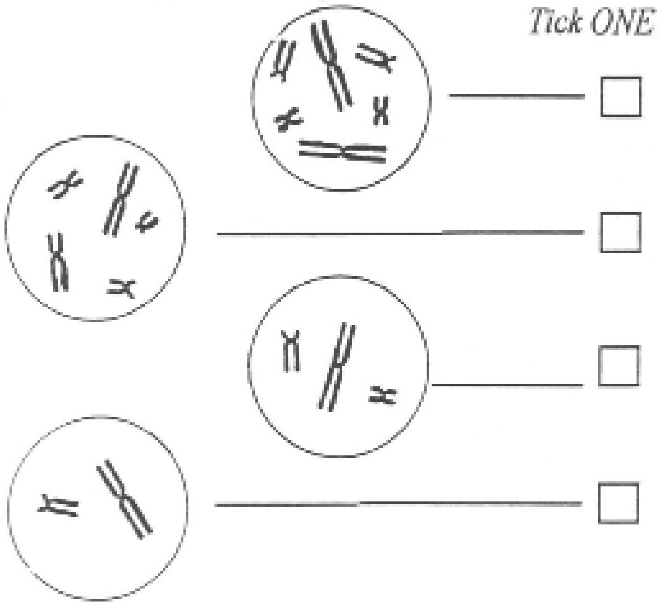
Don't Know ______________________ ☐

Please give the reasons for your answer- --

Appendix 5a: Reproduction continued

Now look at the diagrams below and tick ONE box to show which chromosomes you think would be found in the NEW FERTILISED CELL. Please give reasons for your answer.

Tick ONE Box



Don't Know ——— ☐

Please give the reasons for your answer- --

Part 2

Some simple animals can also reproduce asexually - without the 'combining' of cells described above.

Why do you think an animal that could do this would still need to reproduce sexually as well ?

Please tick ONE box to show whether or not you have any ideas about this. If you have some ideas, please would you explain them.

Tick ONE Box

I have no idea ☐

I have some ideas ☐

I think that --

Appendix 5a: Reproduction continued

Part 3

Plants also need to reproduce.

The alternative ways in which they might do this are listed below.

Please tick ONE box to show how you think plants reproduce, then give reasons for your answer.

	tick ONE box
sexual reproduction	☐
asexual reproduction	☐
both sexual and asexual reproduction	☐
don't know	☐

Please say why you think plants reproduce in this way ------------------------------

----

Appendix 5b: Reproduction - frequency of responses

Analysis Of Responses

The main responses to each question are set out part by part in the following pages. Ambiguous or incomprehensible responses are not included. Nor are views expressed by very few (one or two) individuals - unless grouped under 'other responses'. Occasionally the coding is not exclusive (more than one of the listed views may have been expressed by one person) therefore the total may add up to more than 100% at times.

Number of responses

sample size (number responding to some part of this probe) = 478

Part 1(process of sexual reproduction)	= 477
a) chromosome number in egg and sperm	= 476
b) chromosome number in fertilised egg	= 469
Part 2 (purpose of sexual reproduction)	= 470
Part 3 (sexual reproduction in plants)	= 473

This appendix is in a number of sections:-

Part 1: The process of sexual reproduction
1a - comparison of chromosome number, egg and sperm
1b - chromosome number in fertilised egg

Part 2: The purpose and benefits of sexual reproduction
Part 3: Sexual reproduction in plants

Appendix 5b: Part 1, comparison of egg and sperm

Part 1: Process of sexual reproduction

1a) comparison of chromosomes number in egg and sperm:

If the egg cell contains 3 chromosomes, how many would be found in the sperm cell?

Tick responses (n = 476)

response	number giving this response	% of these responses (476)	% responding to this probe (478)
6 chromosomes (double)	56	11.8	11.7
5 chromosomes (more)	36	7.6	7.5
3 chromosomes (same)*	213	44.7	44.6
2 chromosomes (less)	39	8.2	8.2
don't know	132	27.7	27.6

* *correct answer*

Reasoning (n = 278: 58.4% of those responding to this question gave reasons)

reasons	Number giving this reason	% of those giving this response	% of those giving reasons (n = 278)	% of those answering this probe (n = 478)
more chromosomes (n = 92)	-	-	-	-
*sperm need more chromosomes or genetic information	11	12.0	4.0	2.3
*confusions				
- with terminology	11	12.0	4.0	2.3
- between cell and chromosome	6	6.5	2.2	1.3
- with fertilisation	4	4.3	1.4	<1.0
*no reason	35	38.0	12.6	7.3
the same number of chromosomes (n = 213)				
*need for equal numbers or matching sets of chromosomes	143	67.1	51.4	29.9
[explicitly: numbers in egg and sperm halve before fertilisation]	[63]	[29.6]	[22.7]	[13.2]
*misunderstandings				
- sperm aquires chromosomes from egg	7	3.3	2.5	1.5
- number of chromosomes relates to type or function of cell	2	<1.0	<1.0	<1.0
*confusions				
- between cell and chromosome	3	1.4	1.1	<1.0
- about sex chromosomes	3	1.4	1.1	<1.0
*no reason	32	15.0	11.5	6.7
less chromosomes (n = 39)				
*sperm need less information than egg	3	7.7	1.1	<1.0
*confusion: sex chromosomes	12	30.8	4.3	2.5
*no reason	13	33.3	4.8	2.7

Appendix 5b: Part 1, the fertilised egg

1b) chromosomes number in fertilised egg:
How many chromosomes would be found in the fertilised egg?

Tick responses (n =469)

response	number giving this response	% of these responses (469)	% responding to this probe (478)
6 chromosomes (double)*	202	43.1	42.3
5 chromosomes (more)	39	8.3	8.2
3 chromosomes (same)	40	8.5	8.4
2 chromosomes (less)	36	7.7	7.5
don't know	152	32.4	31.8

** correct answer*

Reasoning (n =262: 55.9% of those responding to this question gave reasons)

reasons	Number giving this reason	% of those giving this response	% of those giving reasons (n = 262)	% of those answering this probe (n = 478)
chromosome number doubles (n = 202)				
*chromosomes or information combine	116	57.4	44.3	24.3
[need for full sets or equal numbers]	[34]	[16.8]	[13.0]	[7.1]
*cells combine				
*no reason	31	15.3	11.8	6.5
	27	13.4	10.3	5.6
more (5) chromosomes (n = 39)				
*recognised need to combine but didn't recognise need for equal contributions	15	38.5	5.7	3.1
*no reason	11	28.2	4.2	2.3
the same number of chromosomes (n = 40)				
*numerous confusions about the process of fertilisation	14	35.0	5.3	2.9
*no reason	15	37.5	5.7	3.1
less chromosomes (n = 36)				
*misunderstandings				
- each parent contributes only 1 chromosome	12	33.3	5.2	2.5
- chromosome number relates to age of the cell	3	8.3	1.1	<1.0
*no reason	12	33.3	5.2	2.5

Appendix 5b: Part 2, the purpose of sexual reproduction

Part 2: The purposes and benefits of sexual reproduction in animals
'Why might an animal which can reproduce asexually also need to reproduce sexually?'

Tick responses (n = 470)

response	number giving this response	% of these responses (470)	% responding to this probe (478)
no idea	332	70.6	69.5
some ideas	133	28.3	27.8

Note: not all those who ticked 'some ideas' gave an explanation; some of those who gave no tick response, or who answered 'no idea' went on to give an explanation.

Explanation (n = 130)

reasons	number giving this reason	% of those giving reasons (130)	% responding to this probe (478)
to mix genes [in order to increase variation] [necessary for survival, adaptation, evolution]	57 [51] [26]	43.8 [39.2] [20.0]	11.9 [10.7] [5.4]
misunderstanding - of the question (response unrelated) - asexual reproduction not possible in animals	 13 7	 10.0 5.4	 2.7 1.5
confusions - between sex, sex cells and biological determination of sex	6	4.6	1.3
disagreements - do not believe that sexual reproduction is necessary in animals	5	3.8	1.0

note: categories not necessarily exclusive

Part 3: Sexual reproduction in plants
How do plants reproduce?

Tick responses (n = 471)

response	number giving this response	% of these responses (471)	% responding to this probe (478)
sexual reproduction	41	8.7	8.6
asexual reproduction	159	33.4	33.3
both types of reproduction*	166	35.2	34.7
don't know	105	22.3	22.0

** correct answer*

Appendix 5b: Part 3, sexual reproduction in plants continued

Reasoning
(n = 284: 60.3% of those responding to this question gave reasons)

reasons	Number giving this reason	% of those giving this response	% of those giving reasons (n = 284)	% of those answering this probe (n = 478)
sexual reproduction only (n = 41)				
*recognition of a mechanism for this	17	41.5	6.0	3.6
[explicitly identify sex cells/organs]	[11]	[26.8]	[3.9]	[2.3]
*confusion				
- don't appear to differentiate between sexual and asexual reproduction	3	7.3	1.1	<1.0
*no reason	11	26.8	3.9	2.3
asexual reproduction only (n = 159)				
*awareness that one plant on its own can reproduce	4	2.5	1.4	<1.0
*no mechanism for *sexual* reproduction - plants can't move	57	35.8	20.1	11.9
*no mechanism for *sexual* reproduction - no sex cells/organs	13	8.2	4.6	2.7
*misunderstanding - fertilisation is 'external' (and so can't be sexual)	17	10.7	6.0	3.6
*misunderstanding - seeds are evidence of *asexual* reproduction	10	6.3	3.5	2.1
*confusions/conflicts - recognise sex cells but don't see a mechanism for the process	14	8.8	4.9	2.9
*no reason	36	22.6	12.7	7.5
both types of reproduction (n = 166)				
* purpose - increasing variation (sexual)	9	5.4	3.2	1.9
* purpose - rapid propagation (asexual)	4	2.4	1.4	<1.0
* purpose - maximise chances of survival	33	19.9	11.6	6.9
*awareness of a mechanism - sexual	35	21.1	12.3	7.3
[pollination]	[14]	[8.4]	[4.9]	[2.9]
[sex cells/organs]	[23]	[13.9]	[8.1]	[4.8]
*awareness of a mechanism - asexual	8	4.8	2.8	1.7
*misunderstanding - seeds as evidence for asexual reproduction	5	3.0	1.8	1.0
*misunderstanding - plants can be sexual or asexual but not both	3	1.8	1.1	<1.0
*confusions - if cross pollination is sexual, is self pollination asexual?	33	19.9	11.6	6.9
*conflict - accept that sexual reproduction occurs but confused as to how, given lack of movement.	4	2.4	1.4	<1.0
*no reason	35	21.1	12.3	7.3