

Mitosis, Meiosis and Fertilization¹

I. Introduction

When you fall and scrape the skin off your hands or knees, how does your body make new skin cells to replace the skin cells that were scraped off? How does each new cell get a complete set of chromosomes? How does a baby get his or her genes? To answer these questions, we need to begin by reviewing what chromosomes and genes are.

Chromosomes and Genes

Each **chromosome** contains a long molecule of DNA. This molecule of DNA contains many genes. A **gene** is a segment of the DNA molecule that gives the instructions for making a protein. For example, one gene gives the instructions for making a protein enzyme which helps to make the pigment melanin, a molecule that contributes to our skin and hair color.

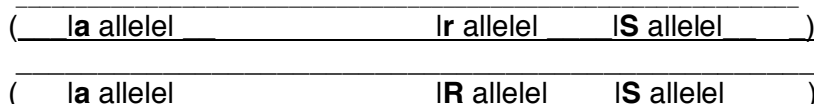
Each cell in your body has two copies of each chromosome. These two copies are called a pair of **homologous chromosomes**. The DNA in both homologous chromosomes contains the same genes at the same locations in the chromosome. However, the two homologous chromosomes may have different versions of a gene.

Different versions of the same gene are called **alleles**. Different alleles give the instructions for making different versions of the protein, and different versions of the protein can result in different characteristics (see examples in the following table).

Allele		Protein		If both homologous chromosomes have this allele, the person has:
A	→	normal enzyme for melanin production	→	normal skin and hair color
a	→	defective enzyme for melanin production	→	very pale skin and hair color (albino)
R	→	normal protein that responds to an odor	→	can smell that odor
r	→	protein that does not respond to the odor	→	can not smell that odor
S	→	normal hemoglobin	→	normal blood
s	→	sickle cell hemoglobin	→	sickle cell anemia (sickle shaped red blood cells that can block blood flow, causing pain and other problems)

Questions

1. Circle everything in the above table that is part of a DNA molecule.
2. The following diagram illustrates just three of the many alleles on a pair of homologous chromosomes in a girl named Tiffany.



Is Tiffany an albino? ___yes ___ no

Does Tiffany have ___ sickle cell anemia or ___ normal blood?

¹ by Drs. Ingrid Waldron, Jennifer Doherty, R. Scott Poethig, and Lori Spindler, Department of Biology, University of Pennsylvania, © 2013; Teachers are encouraged to copy this student handout for classroom use. A Word file (which can be used to prepare a modified version if desired), and Teacher Preparation Notes are available at http://serendip.brynmawr.edu/sci_edu/waldron/.

3. Fill in the blanks of the following sentences.

A chromosome contains one long _____ molecule. Each gene in this molecule gives the instructions for making a _____.

Both chromosomes in a pair of _____ chromosomes have the same _____, but the two chromosomes may have different _____.

Chromosomes that are not homologous have different _____ which give the instructions for making different proteins.

Challenge Question

- ★ Use the information on page 1 to explain why a person with **aa** alleles has very pale skin and hair color. Include the words protein, enzyme and melanin in your explanation.

Each human cell has 23 pairs of homologous chromosomes. Each of these pairs of homologous chromosomes has its own unique set of genes. For example, chromosome 11 has the genes shown in question 2. There are over 1000 additional genes on chromosome 11. In this activity, you will use model chromosomes that represent chromosome 11 and chromosome 4. Chromosome 4 has over 1000 genes, including a gene that can result in dwarfism.

II. Mitosis – How Your Body Makes New Cells

Each of us began as a single cell, so one important question is:

How did that single cell develop into a body with more than a trillion cells?

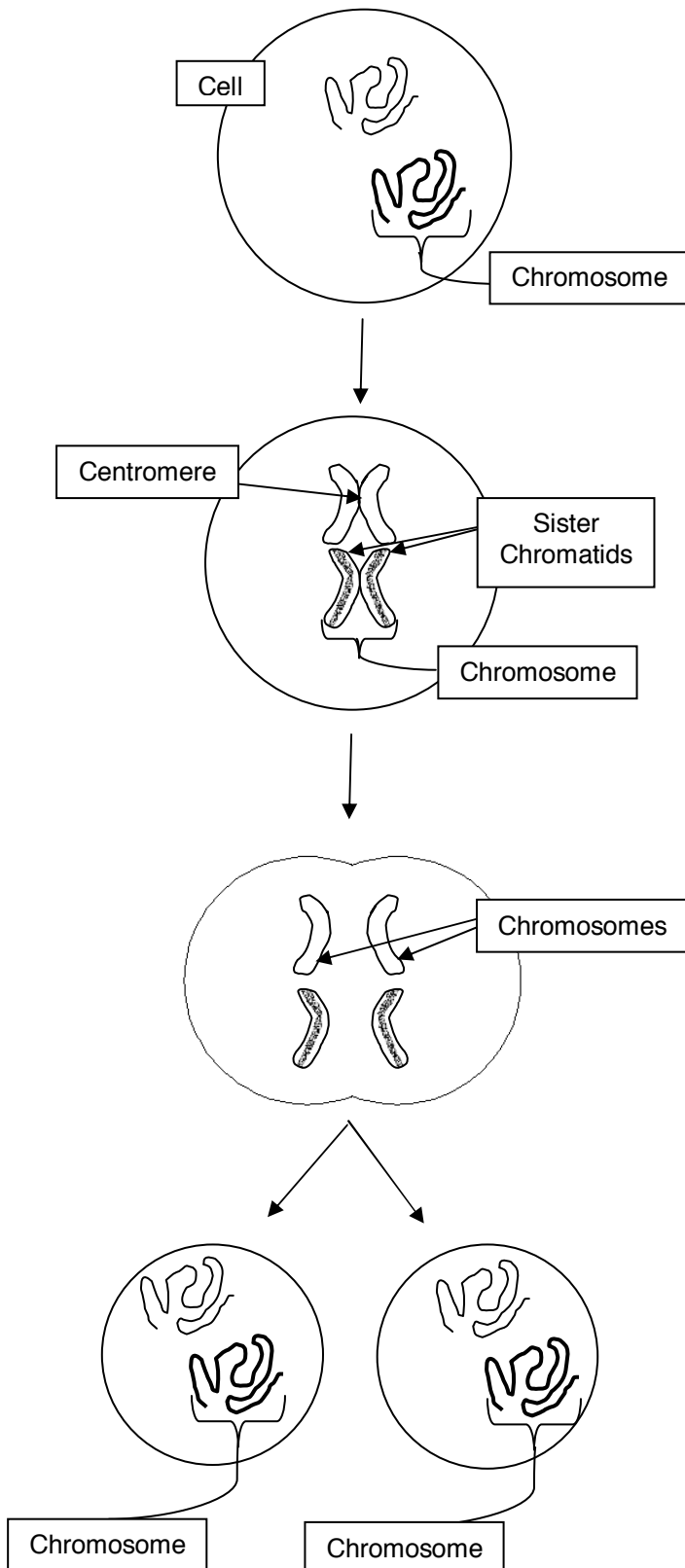
The production of such a large number of body cells is accomplished by many, many repeats of a cycle of **cell division** in which one cell divides to form two cells, then each of these cells divides resulting in a total of four cells, etc. Thus, repeated cell division is needed for growth.

4. Even in a fully grown adult, cells still undergo cell division. Why is this useful? Think about your skin, for example.

The type of cell division that produces almost all the cells in our bodies is called **mitosis**. In mitosis, one cell divides to produce two identical daughter cells. (It may seem odd, but the cells produced by cell division are called daughter cells, even in boys and men.) Each of the daughter cells needs to have a complete set of chromosomes containing an exact copy of all the DNA in the original cell.

Mitosis – How Each Daughter Cell Gets a Complete Set of Chromosomes

The cell shown below has a pair of homologous chromosomes; one chromosome is shown as dark or striped to indicate that it has different alleles from the other homologous chromosome.



Preparation for Mitosis

To get ready for mitosis, the cell makes a copy of the long strand of DNA in each chromosome (**DNA replication**). The two copies of each DNA molecule are attached to each other. (You can't see the two copies until the beginning of mitosis which is shown in the next diagram.)

Beginning of Mitosis

Each copy of the DNA is wound tightly into a compact **chromatid**, and the two chromatids in each chromosome are attached to each other at a **centromere**. The two chromatids are called **sister chromatids** because they are identical.

At the beginning of mitosis, each chromosome consists of a pair of sister chromatids, and the chromosomes are lined up in the center of the cell.

Mitosis continues

Next, the two sister chromatids of each chromosome are separated. After they separate, each chromatid is an independent chromosome.

The cell begins to pinch together in the middle (**cytokinesis**). Cytokinesis proceeds to produce two separate daughter cells.

Mitosis completed

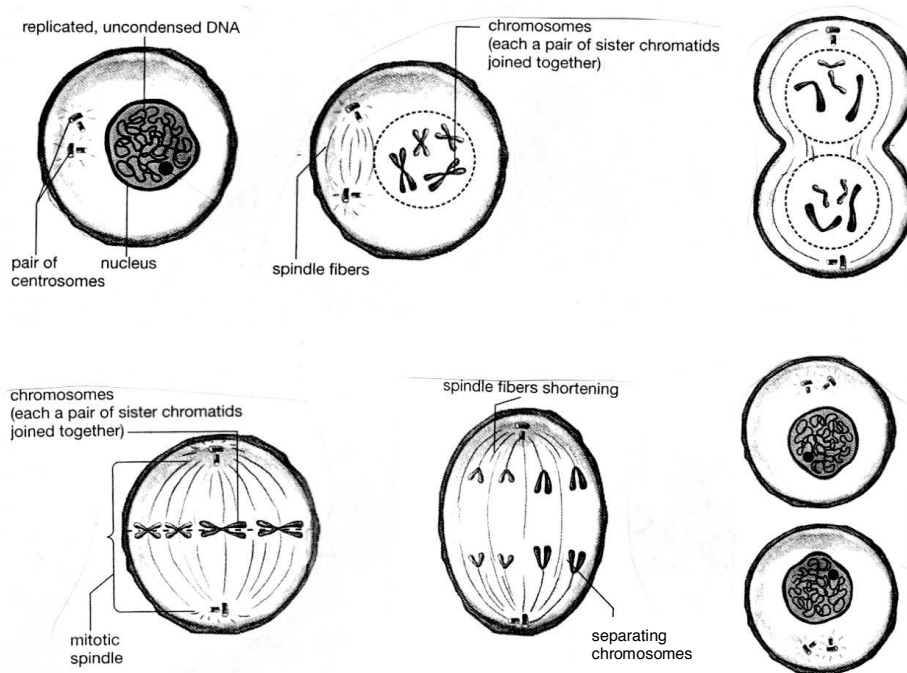
Two new daughter cells have been formed. Each daughter cell has received one copy of each chromosome, so each daughter cell has a complete copy of all the DNA in the original cell.

Questions

5. This fill-in-the-blank question reviews the information from the previous page and provides some additional explanations about 6 steps that are needed for mitosis to occur.

1. In preparation for mitosis, DNA is copied; this is called DNA _____.
2. DNA is wound tightly into compact chromosomes (each with two sister _____). These compact chromosomes are easier to move than the long thin chromosomes in a cell which is not undergoing cell division. **Spindle fibers** which will move the chromosomes begin to form.
3. Spindle fibers attach to the chromosomes and line the chromosomes up in the middle of the cell.
4. Spindle fibers pull the sister _____ apart to form separate chromosomes which are moved toward opposite ends of the cell.
5. In a process called cytokinesis, the cell begins to pinch in half, with one set of chromosomes in each half.
6. Two _____ cells are formed. Each _____ cell has received a complete set of chromosomes. Each chromosome unwinds into a long thin thread so that genes can become active and give the instructions for making proteins.

6. For each of the figures below, give the number of the corresponding step described above. Draw arrows to indicate the sequence of events during cell division. (For simplicity, the figures show cells that have only 4 chromosomes (2 pairs of homologous chromosomes), but the basic process is the same as in human cells which have 46 chromosomes.)



7. Use an * to mark the arrow you drew which shows when sister chromatids separate to form individual chromosomes.

Circle and label each pair of homologous chromosomes (HC) in step 3.

8. Each of the daughter cells shown in step 6 can divide to produce two new cells. What needs to happen before these cells will be ready for mitosis?

Modeling Mitosis

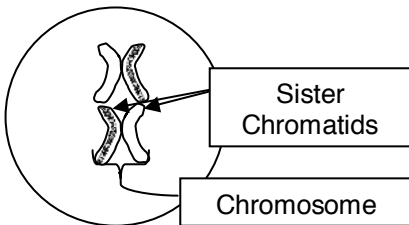
To model mitosis you will use pairs of model chromosomes to represent the pairs of homologous chromosomes. Each model chromosome will have two sister chromatids (as shown in the second drawing on page 3). Thus, you will model mitosis, beginning after the DNA has been copied and wound tightly into sister chromatids.

- Find two model chromosomes that have the two different alleles for the gene that can result in albinism (**A** for normal melanin production and normal skin and hair color and **a** for albinism; these model chromosomes also have **S** and **R** alleles to remind you of the many additional genes on each chromosome, but you will only be working with the **A** and **a** alleles).

Both model chromosomes in this pair are the same color, to indicate that these are a pair of homologous chromosomes so they both have the same genes. One model chromosome has a stripe on both chromatids and the other model chromosome has no stripe; this indicates that, although they have the same genes, the two homologous chromosomes have different alleles for many of the genes.

- Together with your partner, use this pair of model chromosomes to demonstrate how the two chromosomes line up at the beginning of mitosis (see figure on page 3). Then demonstrate how the sister chromatids of each chromosome separate into two separate chromosomes, one of which goes to each daughter cell. Use your arms to represent the spindle fibers that pull the sister chromatids apart.

9. You will need to put your model chromosomes back together for the next part of this activity. The diagram shows how your partner has put them together. You realize that this arrangement of the model chromosomes could never occur in a real cell. What is wrong? Explain why sister chromatids could not have different alleles.



- Next, find two model chromosomes in your group that have the two different alleles for the gene that can result in dwarfism (**D** for dwarfism and **d** for normal height). Use all four chromosomes to model the steps in mitosis. Demonstrate how the four chromosomes line up at the beginning of mitosis and how the sister chromatids of each chromosome separate during mitosis.

10. Describe your results by completing the following table.

	AA or Aa or aa?	DD or Dd or dd?
Which alleles were present in the original cell (before DNA replication)?	Aa	
Which alleles are present in each daughter cell produced by mitosis?		

Are the alleles in the daughter cells produced by mitosis the same as or different from the alleles in the original cell?

11. Explain how each daughter cell produced by mitosis receives exactly the same alleles as the original cell had.

12. Why is it useful for the spindle fibers to line up the chromosomes in the middle of the cell at the beginning of mitosis?

III. Meiosis – How Your Body Makes Sperm or Eggs

Almost all the cells in your body were produced by mitosis. The only exception is sperm or eggs which are produced by a different type of cell division called **meiosis**.

During **fertilization** the sperm and egg unite to form a single cell called the **zygote** which contains chromosomes from both the sperm and egg. The zygote undergoes mitosis to begin the development of the embryo which eventually becomes a baby.

Why your body can not use mitosis to make sperm or eggs

13. Remember that a typical cell in your body has 46 chromosomes (23 pairs of homologous chromosomes). Suppose that human sperm and eggs were produced by mitosis. How many chromosomes would each sperm or egg have? _____

14. If a sperm of this type fertilized an egg of this type, and both the sperm and egg contributed all of their chromosomes to a zygote, how many chromosomes would the resulting zygote have? _____

15. In humans, how many chromosomes should a zygote have, so the baby's body cells will each have a normal set of chromosomes? _____

16. Obviously, if the body used mitosis to make sperm and eggs, the resultant zygote would have too many chromosomes to produce a normal baby. To produce a normal zygote, how many chromosomes should each sperm and egg have? _____

To produce the needed number of chromosomes in sperm and eggs, meiosis reduces the number of chromosomes by half. For example, in humans each sperm and each egg produced by meiosis has only 23 chromosomes, including one chromosome from each pair of homologous chromosomes.

When an egg and sperm are united during fertilization, the resulting zygote has 23 pairs of homologous chromosomes, one in each pair from the egg and one from the sperm. Thus, the zygote has 46 chromosomes, and when the zygote undergoes mitosis to begin to form an embryo, each cell will have the normal number of 46 chromosomes.

Cells that have two copies of each chromosome (i.e. cells that have pairs of homologous chromosomes) are called **diploid** cells. Most of the cells in our bodies are diploid cells.

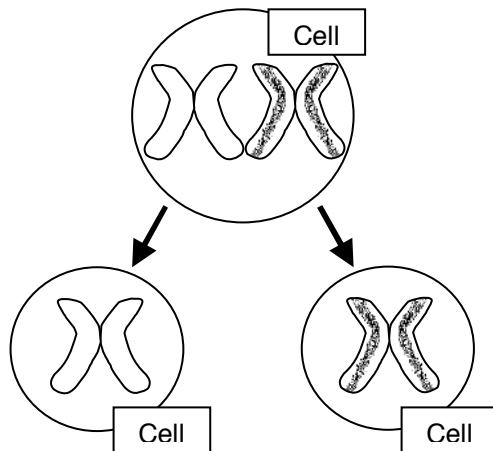
17. Cells that only have one copy of each chromosome are called **haploid** cells. Which types of cells in our bodies are haploid?

Meiosis – Two cell divisions to produce haploid sperm or eggs

Before meiosis, the cell makes a copy of the DNA in each chromosome. Then, during meiosis there are two cell divisions, **Meiosis I** and **Meiosis II**. Meiosis reduces the chromosome number by half and produces four haploid daughter cells.

Meiosis I

Meiosis I is different from mitosis because homologous chromosomes line up next to each other and then the two homologous chromosomes separate, as shown below. This produces daughter cells with half as many chromosomes as the parent cell, i.e. haploid cells. Notice that each daughter cell has a different chromosome from the homologous pair of chromosomes.

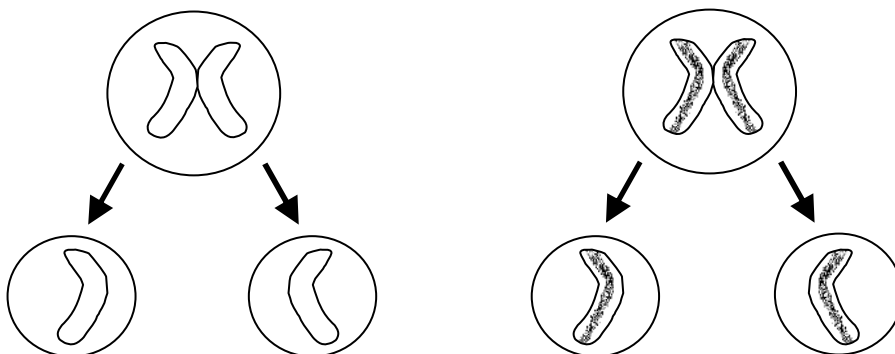


18. Compare the chromosomes in the two daughter cells produced by Meiosis I. Do these chromosomes have the same alleles for each gene? How do you know?

19. Label the sister chromatids of the chromosome in the first daughter cell shown above.

Meiosis II

Meiosis II is like mitosis, since the sister chromatids of each chromosome are separated. As a result, each daughter cell gets one copy of a chromosome from the pair of homologous chromosomes that was in the original cell.



20. In the diagram above, label the cells which represent the sperm or eggs produced by meiosis.

Modeling Meiosis

- Find two model chromosomes that have the two different alleles for the gene for albinism (**A** for normal skin and hair color and **a** for albinism). Use these model chromosomes to model each step of meiosis, as shown above. Repeat until you are confident that you understand the differences between Meiosis I and Mitosis and the differences between Meiosis I and Meiosis II.

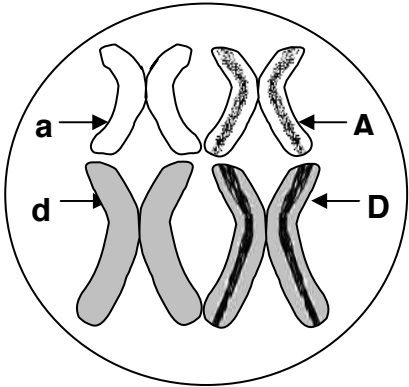
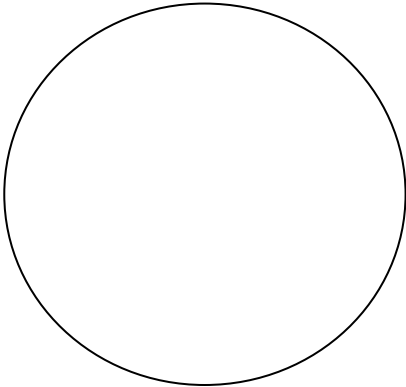
21. Draw diagrams to show the difference in the way that a pair of homologous chromosomes is lined up in a cell at the beginning of Meiosis I vs. the beginning of Mitosis.

22. You have been modeling meiosis beginning with a diploid cell that has the genetic makeup **Aa**. The genetic makeup of the haploid sperm or eggs produced by meiosis is: **A** or **a** **AA** or **aa** **Aa**

- Next, find two model chromosomes that have the two different alleles for the gene for dwarfism (**D** for dwarfism and **d** for normal height). Use all four model chromosomes to model meiosis in a cell which has two pairs of homologous chromosomes, with the genetic makeup **AaDd**.

Begin by lining up the model chromosomes as shown in the figure below; model what would happen during meiosis. Next, model meiosis for the other possible way of lining up the model chromosomes at the beginning of Meiosis I.

23. Complete this chart to summarize the results of your modeling.

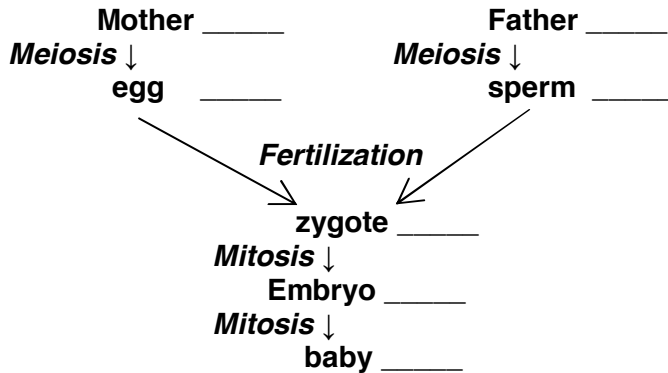
<p>Chromosomes at the beginning of Meiosis I</p>		
<p>Genetic makeup of sperm or eggs</p>	<p>_____ or _____</p>	<p>_____ or _____</p>

24. Explain the reasons why different sperm or eggs produced by the same person can have different genetic makeup (i.e. different alleles).

25. Describe the differences between mitosis and meiosis.

26. What are some similarities between cell division by meiosis and cell division by mitosis?

27. The following diagram provides an overview of the information covered thus far. Review the diagram, and fill in the correct number of chromosomes per human cell in each blank.

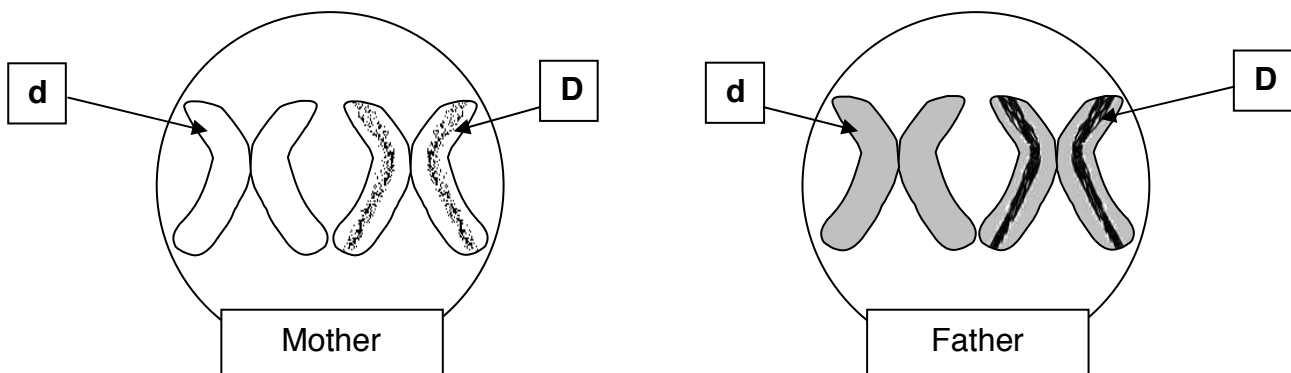


IV. Analyzing Meiosis and Fertilization to Understand Genetics

In this section you will investigate how events during meiosis and fertilization determine the genetic makeup of the zygote, which in turn determines the genetic makeup of the baby that develops from the zygote.

You already know that sisters or brothers can have different characteristics, even though they have the same parents. One major reason for these different characteristics is that the processes of meiosis and fertilization result in a different combination of alleles in each child.

To begin to understand this genetic variability, you will model meiosis and fertilization for a very simplified case where there is only one pair of homologous chromosomes per cell and you will consider just one gene on this chromosome. In both the mother and the father, this gene will have different alleles on the two homologous chromosomes, as shown in the figure below. (Alternatively, you may have four model chromosomes similar to those shown, but labeled **a** and **A**).



28. Considering just the labeled alleles, how many different types of eggs will be produced by meiosis?

List the genetic makeup of the different types of eggs.

The father will also produce sperm with different alleles. The different types of sperm can fertilize the different types of egg to result in zygotes with different combinations of chromosomes from the mother and the father.

Modeling Meiosis and Fertilization

- One of you should be the father and demonstrate how meiosis produces different types of sperm, and your partner should be the mother and demonstrate how meiosis produces different types of eggs. Next you should use one of the sperm to fertilize one of the eggs to produce a zygote. The resulting zygote will have a pair of homologous chromosomes including one chromosome from the egg and one from the sperm.

Try to produce as many different types of zygotes as you can by pairing each type of sperm with each type of egg.

29. List the three different combinations of the labeled alleles that can occur in the zygotes produced by fertilization.

30. Notice that each parent has two different alleles for this gene, but some of the children will have two copies of the same allele. Explain how a child can have a different genetic makeup than either parent.

In the simple example you have modeled, meiosis and fertilization can produce zygotes with three different combinations of the two alleles for one gene. Each person has thousands of genes on 23 pairs of homologous chromosomes, so the children produced by a couple could have many more different genetic combinations. As a result of the different ways that the 23 pairs of homologous chromosomes can line up during Meiosis I, more than 8 million different combinations of chromosomes could be found in the different eggs or sperm produced by one person. If each different type of egg from one mother could be fertilized by each different type of sperm from one father, they could produce zygotes with approximately 70 trillion different combinations of chromosomes! You can see why no two people are genetically alike, except for identical twins who both develop from the same zygote.

Challenge Question

- ★ Sally and Harry fall in love. They introduce Sally's identical twin, Emily, to Harry's identical twin, Ken. Soon there is a double wedding where Sally marries Harry and Emily marries Ken. Both Sally and Emily get pregnant. They wonder "Will their babies look exactly alike?" Answer their question, and explain your reasoning. (Hint: Think about your results from modeling meiosis and fertilization.)

V. A Mistake in Meiosis Can Cause Down Syndrome

Sometimes, meiosis does not happen perfectly, so the chromosomes are not divided completely equally between the daughter cells produced by meiosis. For example, an egg or a sperm may receive two copies of the same chromosome.

31. If a human egg receives two copies of a chromosome, and this egg is fertilized by a normal sperm, how many copies of this chromosome would there be in the resulting zygote? _____

32. How many copies of this chromosome would there be in each cell in the resulting embryo? _____

When a cell has three copies of a chromosome, the extra copies of the genes on this chromosome result in abnormal cell function and abnormal embryonic development. To understand how an extra copy of one chromosome could result in abnormalities, remember that each chromosome has genes with the instructions to make specific types of proteins, so the extra chromosome could result in too many copies of these specific proteins. Think about what might happen if you added too much milk to a box of macaroni and cheese. The macaroni and cheese would have too much liquid and be runny instead of creamy. Cells are much more complicated than mac and cheese, and a cell cannot function properly when there are too many copies of some types of proteins due to an extra copy of one of the chromosomes. When the cells in an embryo do not function properly, the embryo develops abnormalities.

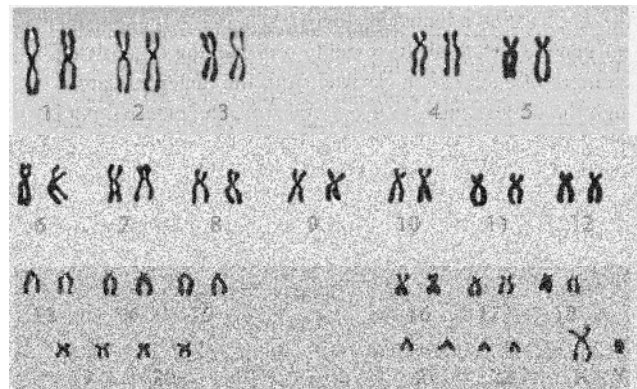
In most cases, an embryo which has an extra chromosome in each cell develops such severe abnormalities that the embryo dies, resulting in a miscarriage. However, some babies are born with an extra copy of chromosome 21 in each cell. This results in the condition known as **Down Syndrome** with multiple abnormalities, including mental retardation, a broad flat face, a big tongue, short height, and often heart defects.

33. The figure below shows a **karyotype** from a normal boy. A karyotype is a photograph of a magnified view of the chromosomes from a human cell, with pairs of homologous chromosomes arranged next to each other and numbered. An extra copy of any of the chromosomes in the top row results in such severe abnormalities that the embryo always dies. In contrast, an extra copy of chromosome 21 results in less severe abnormalities so the embryo can often survive to be born as a baby with Down syndrome. What do you think is the reason for this difference?

34. In the karyotype, each chromosome has double copies of its DNA, contained in a pair of sister chromatids linked at a centromere. Label the sister chromatids and the centromere in chromosome 3 in the karyotype.

35. The shape of the chromosomes in the karyotype indicates that these chromosomes came from

- a cell that is not dividing
 - a cell that is ready to begin mitosis
 - a cell that is near the end of mitosis
- (Hint: See the figure on page 3.)



Adapted from Concepts of Genetics 8e
by Klug, Cummings, and Spencer