Mitosis – How Each New Cell Gets a Complete Set of Genes[1]

Introduction – Chromosomes and Genes

- Each cell in your body contains chromosomes.
- Each **chromosome** contains a long molecule of DNA. Each DNA molecule contains many genes.
- A **gene** is a segment of a DNA molecule that gives the instructions for making a protein.
- Different versions of the same gene are called **alleles**. Different alleles give the instructions for making different versions of a protein. The following table illustrates this for three human genes.

Allele	→	**Protein**
A	→	Normal enzyme for producing melanin, a pigment molecule that gives color to our skin and hair
a	→	Defective enzyme that cannot make melanin
S	→	Normal hemoglobin
s	→	Sickle cell hemoglobin
L	→	Defective enzyme that cannot dispose of a harmful molecule that is produced by the metabolism of alcohol
l	→	Normal enzyme that disposes of harmful molecule produced by alcohol metabolism

1. In the above table, circle each symbol that represents part of a DNA molecule.

Each cell has two copies of each chromosome; the two copies of a chromosome are called a pair of **homologous chromosomes**. The DNA in both homologous chromosomes contains the same genes at the same locations in the chromosome. The two copies of each gene may have the same alleles or different alleles.

This table shows how different **genotypes** (i.e. different combinations of alleles) result in the production of different proteins which in turn can result in different **phenotypes** (i.e. different observable characteristics).

Genotype	→	**Protein**	→	**Phenotype** (characteristics)
AA or **Aa**	→	Enough normal enzyme to make melanin in skin and hair	→	Normal skin and hair color
aa	→	Defective enzyme for melanin production	→	Very pale skin and hair color (albino)
SS or **Ss**	→	Enough normal hemoglobin to prevent red blood cells from becoming sickle shaped	→	Normal blood (no sickle cell anemia)
ss	→	Sickle cell hemoglobin	→	Sickle cell anemia (sickle shaped red blood cells can block blood flow in the smallest blood vessels, causing pain and other problems)
LL or **Ll**	→	Defective enzyme[2]	→	Skin flush and discomfort after drinking alcohol
ll	→	Normal enzyme	→	No flush or discomfort after drinking alcohol

[1] By Drs. Ingrid Waldron, Jennifer Doherty, R. Scott Poethig, and Lori Spindler, Department of Biology, University of Pennsylvania, © 2014; Teachers are encouraged to copy this Student Handout for classroom use. A Word file for this Student Handout and Teacher Preparation Notes with instructions for making the model chromosomes and background information are available at http://serendip.brynmawr.edu/sci_edu/waldron/.

[2] The active enzyme consists of four normal proteins bound together. In a person with the **Ll** genotype**,** the normal protein (coded for by the **l** allele) combines with the defective protein (coded for by the **L** allele) to form inactive enzyme.

2. 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 genes on the two chromosomes may have different _____.

3. Explain why a person with **aa** genotype has very pale skin and hair color. Include the words 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, this diagram shows alleles for two of the many genes on human chromosome 11 and alleles for one of the many genes on chromosome 12. There are over 1000 additional genes on each of these chromosomes.

A allele **s** allele	**L** allele
a allele **s** allele	**l** allele

4. Suppose that a man named Jim has the alleles shown in the above diagram.

Is Jim an albino? ___yes ___ no

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

Does Jim experience skin flush and discomfort after drinking alcohol? ___yes ___ no

Mitosis – How New Cells Are Made

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?

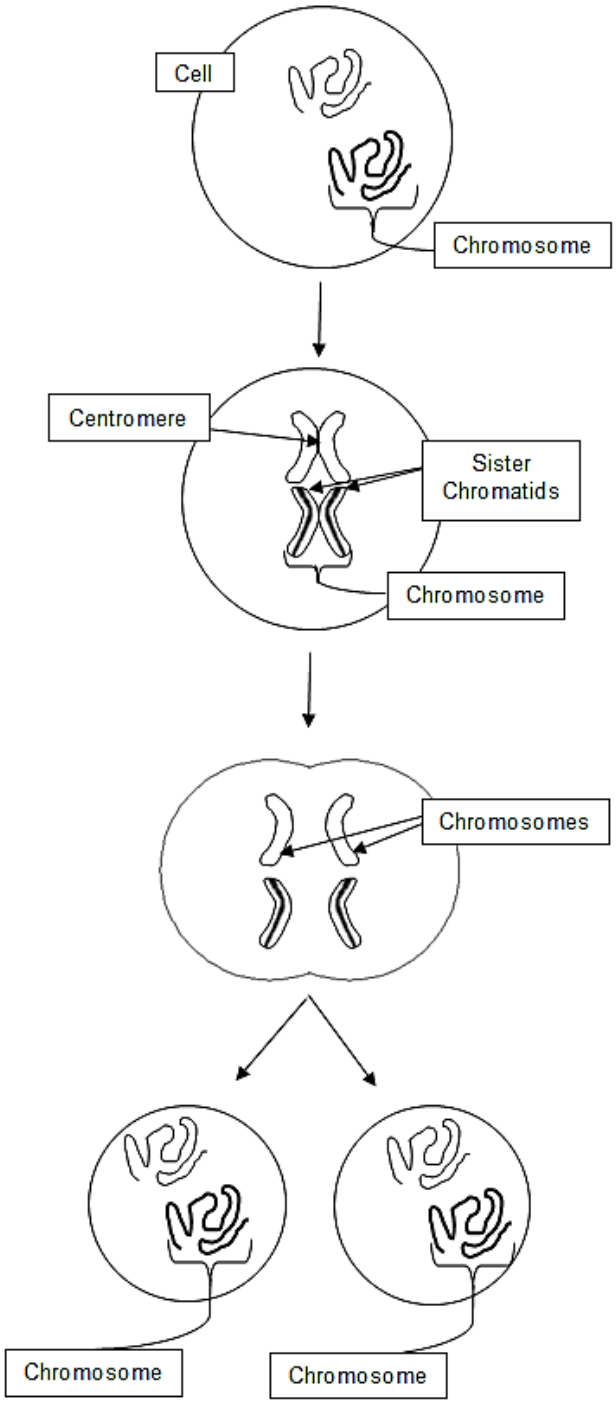
The production of such a large number of body cells is accomplished by many, many repeats of a cycle of **cell division** in which one cell divides to form two cells, then each of these cells divides resulting in a total of four cells, etc. Thus, repeated cell division is needed for growth.

5. Even in an adult, some cells continue to divide. Why is cell division useful even in an adult who is no longer growing? (Hint: Think about what happens when you have an injury that scrapes off some of your skin.)

Almost all the cells in our bodies are produced by **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 daughter cell needs to have a complete set of chromosomes containing all the genes that are needed to produce the many proteins that carry out crucial cell functions.

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

This figure shows mitosis for a cell that has only one pair of homologous chromosomes. One chromosome is shown as dark or striped to indicate that there are different alleles for many of the genes on the two homologous chromosomes.



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 drawing.)

Beginning of Mitosis

Each copy of the DNA is wound tightly into a compact **chromatid**. The two chromatids in each chromosome have exactly the same alleles and are called **sister chromatids**. The sister chromatids are attached at a **centromere**.

At the beginning of mitosis, 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.

Cytokinesis

The cell pinches together in the middle, separating the cytoplasm into two daughter cells, each with a complete set of chromosomes. Thus, each daughter cell has a complete copy of all the genes in the original cell.

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

A. In preparation for mitosis, DNA is copied; this is called DNA _____.

B. 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.

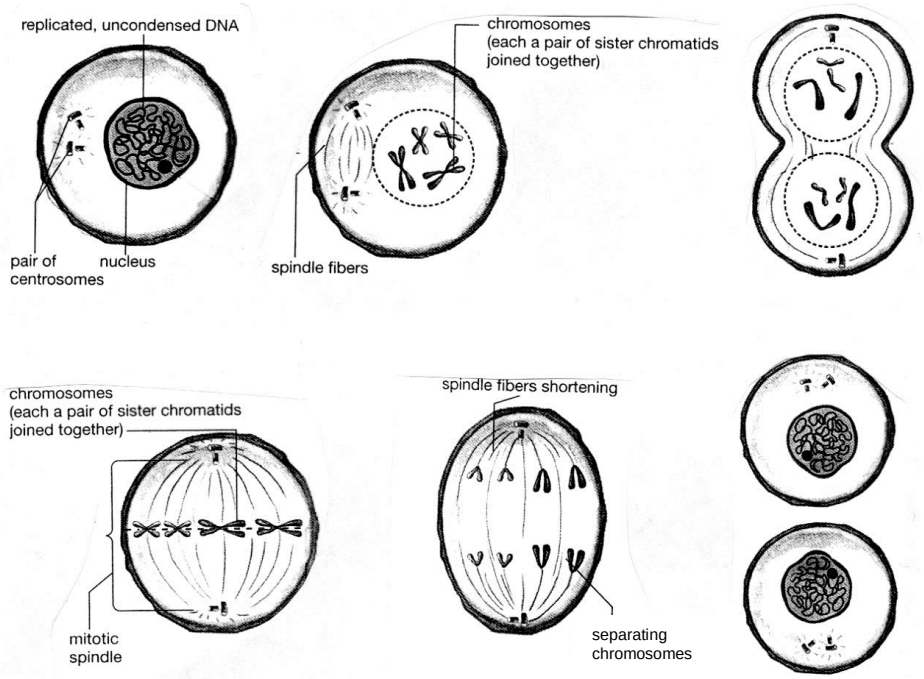
C. Spindle fibers attach to the chromosomes and line up the chromosomes in the middle of the cell.

D. Spindle fibers pull the sister _____ apart to form separate chromosomes which are moved toward opposite ends of the cell.

E. In a process called _____, the cell pinches in half, with one complete set of chromosomes in each half.

F. 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.

7. For each of the figures below, give the letter of the corresponding step described above. Draw arrows to indicate the sequence of events during cell division. (The figures show mitosis for a cell that has only 4 chromosomes (2 pairs of homologous chromosomes). The basic process is the same in a human cell which has 46 chromosomes.)



8. Use an * to mark the arrow you drew which shows when sister chromatids separate to form individual chromosomes.
- Circle each pair of homologous chromosomes in step C.

9. What would need to happen before each cell shown in step F would be ready for mitosis?

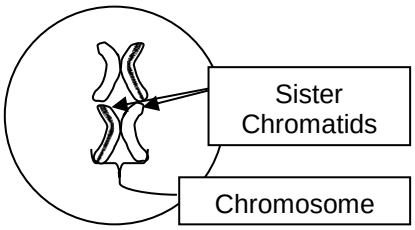
Modeling Mitosis

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 cell in the figure 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 two different alleles (**A** and **a**) for the gene that can result in albinism and two different alleles (**S** and **s**) for the gene that can result in sickle cell anemia. Both model chromosomes in this pair should be the same color. One model chromosome has a stripe on both chromatids and the other model chromosome has no stripe; this indicates that, although these too homologous chromosomes have the same genes, they have different alleles for many of the genes.

- Together with your partner, use this pair of model chromosomes to demonstrate how the two chromosomes are lined up at the beginning of mitosis (see figure on page 3). Sit across from your partner and use your arms to represent the spindle fibers that line up the chromosomes. Then demonstrate how the sister chromatids of each chromosome are separated into two separate chromosomes which go to opposite ends of the cell. Now the cell is ready for cytokinesis which will produce two daughter cells, each with a complete set of chromosomes.

10. 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 sensitivity to alcohol (**L** and **l**). Use both pairs of homologous 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 are separated during mitosis (see diagrams on page 4).

11. Describe your results by completing the following table.

	AA or **Aa** or **aa**?	**SS** or **Ss** or **ss**?	**LL** or **Ll** or **ll**?
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?

12. Each of the cells in your skin, brain, and other parts of your body have a complete set of chromosomes with the same genes and the same alleles that were present in the single cell that developed into your body. Explain how these billions of genetically identical cells were produced.