12
Meiosis and Genetic Diversity

Learning Objectives

In this chapter, you will learn:

- ➜ How Meiosis Works
- ➜ How Meiosis Generates Genetic Diversity

Overview

Meiosis allows parents to pass on genetic information to their offspring. Meiosis helps accomplish this task while also maintaining a consistent number of chromosomes in the offspring *and* creating genetic diversity in the species. This chapter reviews the process of meiosis and how meiosis accomplishes these tasks. This chapter also compares the similarities and differences between meiosis and mitosis.

How Meiosis Works

Meiosis is the process of cell division that is used in gamete formation. Meiosis forms **haploid** (n) gametes from **diploid** ($2n$) parent cells. This helps maintain the proper number of chromosomes in the offspring. When a haploid (n) egg is fertilized by a haploid (n) sperm, the resulting zygote has the correct diploid ($2n$) number of chromosomes.

Unlike mitosis, which results in the creation of two genetically identical diploid daughter cells, meiosis has two rounds of cell division (meiosis I and meiosis II) that result in the creation of four genetically different haploid gametes.

When determining the number of chromosomes in a cell, count the number of centromeres—this will tell you the number of chromosomes. Be aware that before DNA replication, a chromosome will have one chromatid, and after DNA replication, a chromosome will have two chromatids.

Meiosis I

The first round of cell division in meiosis is called **meiosis I**, and it is sometimes referred to as a reduction division. Meiosis I consists of four stages: prophase I, metaphase I, anaphase I, and telophase I.

- In the prophase stage of mitosis, the nuclear membrane breaks down and the chromosomes condense and become visible. This also occurs in the **prophase I** stage of meiosis. However, unlike in mitosis, homologous chromosomes pair up and **genetic recombination** (also known as **crossing-over**) can occur in prophase I of meiosis. This has profound effects on genetic diversity, which will be discussed later in this chapter.
- In the metaphase stage of mitosis, chromosomes line up in a *single* column along the center of the cell. In the **metaphase I** stage of meiosis, however, chromosomes line up in homologous *pairs* along the center of the cell.
- During the anaphase stage of mitosis, the sister *chromatids* in each chromosome separate and move toward opposite ends of the cell. Each of these sister chromatids has its own centromere after this separation, so the number of chromosomes in the cell is doubled by the end of the anaphase stage of mitosis. In the **anaphase I** stage of meiosis, *pairs of homologous chromosomes* separate. There are the same number of chromosomes at the end of the anaphase I stage of meiosis as there are at the beginning of this stage.
- During the telophase stage of mitosis, two new nuclei are formed. This is followed by cytokinesis and results in two *diploid* cells. In the **telophase I** stage of meiosis, two new nuclei are formed. When followed by cytokinesis, this results in two *haploid* cells, as shown in Figure 12.1.

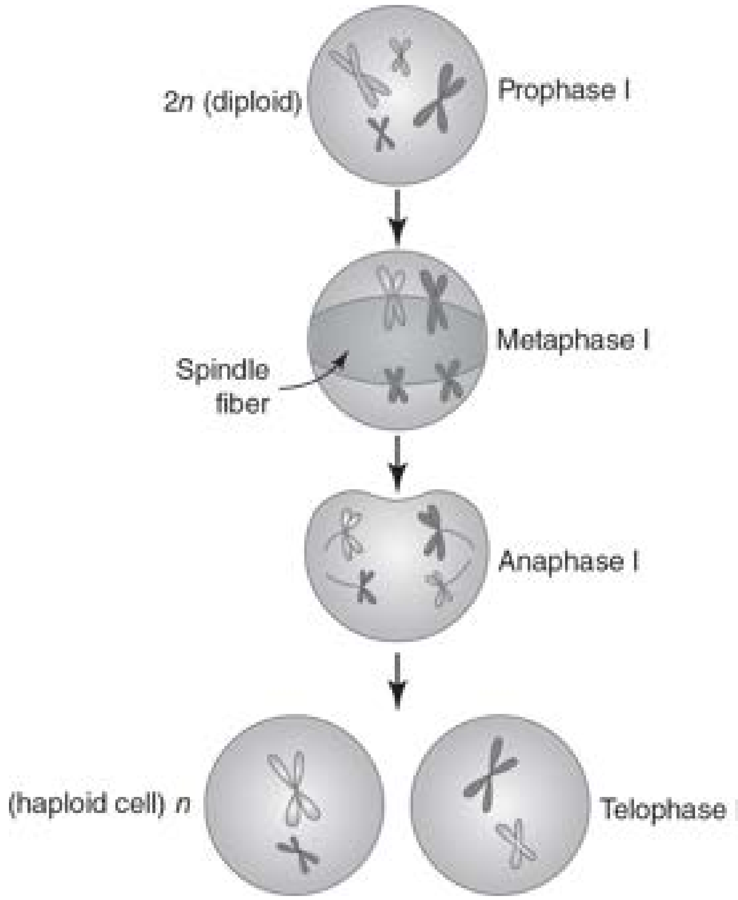


Figure 12.1 Meiosis I

Meiosis II

The second round of cell division in meiosis is called **meiosis II**, and it is very similar to mitosis. Meiosis II consists of four stages: prophase II, metaphase II, anaphase II, and telophase II. However, unlike in mitosis, the events of meiosis II are not preceded by the replication of DNA.

> DNA is replicated prior to the start of mitosis and is followed by one cell division, resulting in two diploid cells at the end of mitosis. However, while DNA is also replicated before the start of meiosis I, it is then followed by *two* cell divisions (meiosis I and meiosis II). This is the reason why the final result of meiosis is four haploid cells.

- In **prophase II** of meiosis II, chromosomes again condense and become visible.
- During **metaphase II**, chromosomes line up in a single line along the center of each cell, similar to how chromosomes line up in the metaphase stage of mitosis.
- Then, in **anaphase II**, sister chromatids separate and move to opposite ends of the cell. Each sister chromatid will have its own centromere once this separation has occurred. At the end of anaphase II, these separated sister chromatids are now considered separate chromosomes.
- **Telophase II** then splits each of the two cells in half, resulting in four cells. At the end of meiosis II, there are four haploid gametic cells, as shown in Figure 12.2.

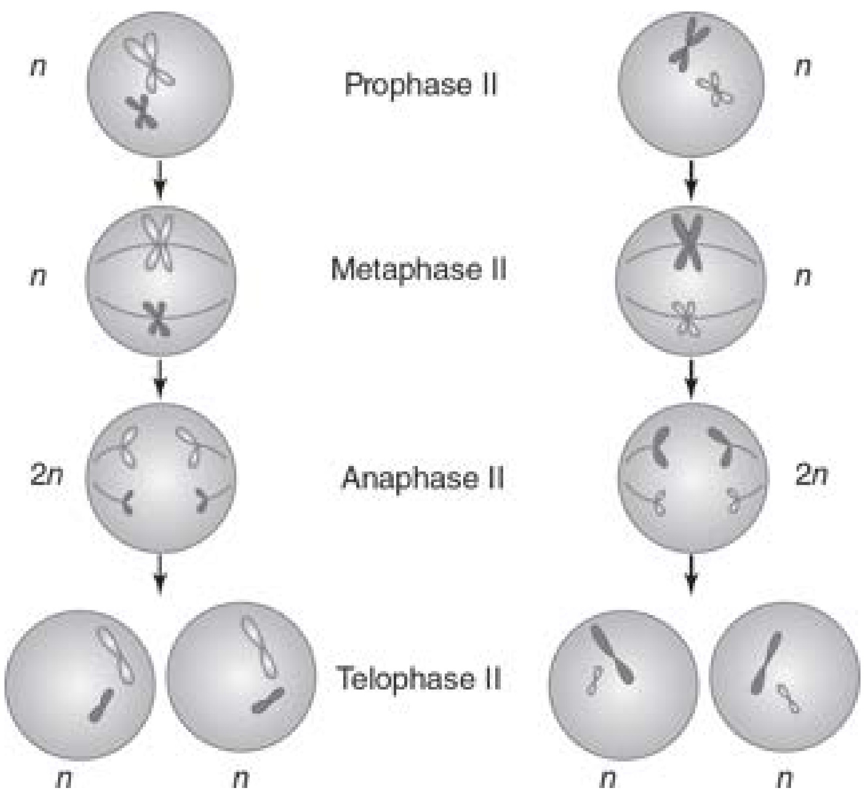


Figure 12.2 Meiosis II

The process of meiosis results in gametes with the haploid number of chromosomes. This is important because the joining of two haploid gametes in fertilization produces a diploid zygote. Together, meiosis and fertilization ensure consistency in the number of chromosomes from one generation to the next.

How Meiosis Compares to Mitosis

Table 12.1 summarizes the similarities and differences between mitosis and meiosis.

Table 12.1 Mitosis vs. Meiosis

	Mitosis	Meiosis
Purpose	Reproduction in asexually reproducing organisms; growth; repair	Reproduction in sexually reproducing organisms
DNA Replication	Occurs once (before the start of mitosis)	Occurs once (before the start of meiosis I)
Cell Division	One round	Two rounds
Result	Two genetically identical, diploid somatic cells	Four genetically different, haploid gametes

How Meiosis Generates Genetic Diversity

Meiosis generates genetic diversity in multiple ways. In the prophase I stage of meiosis, homologous chromosomes pair up in a process called **synapsis** to form **tetrads**.

TIP

To recall the meaning of *tetrad*, remember that the prefix *tetra-* means "four." During synapsis, two homologous chromosomes (with two chromatids each) pair up. This *tetra*d has *four* chromatids.

Once the tetrads are formed, homologous chromosomes may exchange genetic information through the process of genetic recombination (or crossing-over). This generates new combinations of genetic material on each chromatid that may be passed on to the offspring. This increases the genetic diversity of the species, as shown in Figure 12.3.

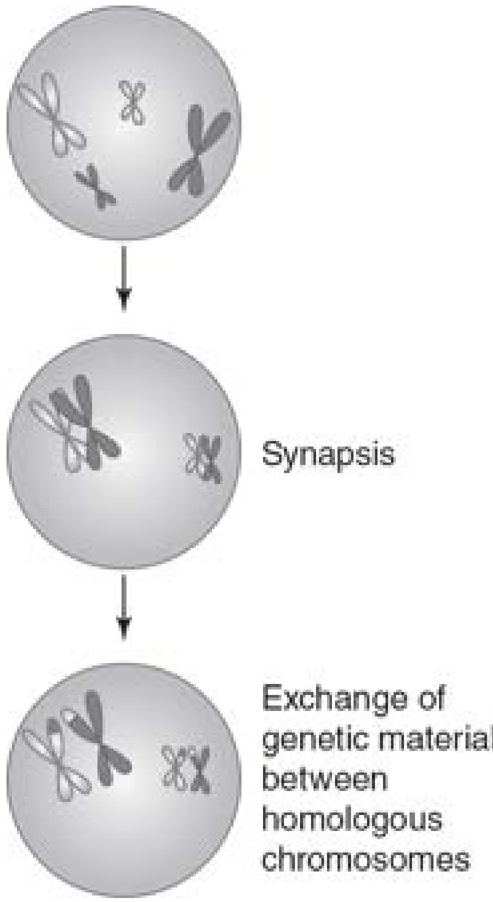


Figure 12.3 Genetic Recombination (Crossing-Over)

The frequency of genetic recombination events can be used to estimate the distance between genes that are on the same chromosome. Genes that are farther apart will have a higher recombination frequency, and genes that are closer to each other will have a lower recombination frequency. The frequency of genetic recombination between genes on the same chromosome can be used to generate genetic maps that show the relative positions of genes on chromosomes. Genes that are close together on the same chromosome tend to be inherited together more often (since the frequency of recombination between them is lower) and are referred to as **linked genes**.

Sometimes, genetic recombination may occur between nonhomologous chromosomes. These events create mutations called **translocations**. While translocations can also generate new combinations of genetic material, if they occur in the middle of a gene, they may inactivate it, resulting in an unfavorable phenotype.

Genetic diversity can also be generated during the metaphase I stage of meiosis. Recall that during metaphase I, homologous pairs of chromosomes line up along the center of the cell. Each pair of chromosomes lines up and assorts independently, with different pairs having the paternal chromosome (from the male parent) on one side and the maternal chromosome (from the female parent) on the other side. For example, if an organism has two pairs of chromosomes, each time meiosis occurs, the two pairs may assort independently, resulting in a different combination of genetic material being passed on to the offspring, as shown in Figure 12.4.

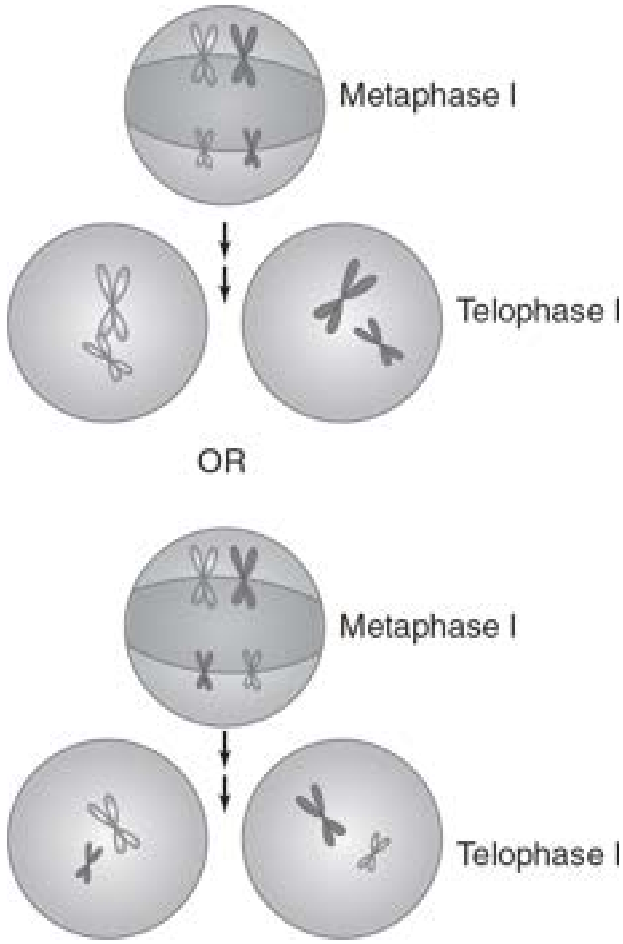


Figure 12.4 Independent Assortment of Chromosomes in Metaphase I of Meiosis

Occasionally during the anaphase I stage of meiosis, pairs of homologous chromosomes fail to separate and will instead move to the same side of the cell, eventually ending up in the same gamete. This is called **nondisjunction**. If the resulting gametes are fertilized, this can result in an **aneuploidy**, which is when there is an atypical number of chromosomes. One example of an aneuploidy is Down syndrome, also known as trisomy 21, which can result when an individual has three copies of chromosome 21 instead of two copies.

Practice Questions

Multiple-Choice

1. Which of the following correctly describes the products of meiosis?

   (A) two genetically identical diploid cells
   (B) two genetically different diploid cells
   (C) four genetically identical haploid cells
   (D) four genetically different haploid cells

2. An organism's diploid number is 28. Which of the following is a correct statement about this organism?

   (A) Its somatic cells would have 14 chromosomes, and its gametes would have 28 chromosomes.
   (B) Its somatic cells would have 28 chromosomes, and its gametes would have 14 chromosomes.
   (C) Both its somatic cells and its gametic cells would have 14 chromosomes.
   (D) Both its somatic cells and its gametic cells would have 28 chromosomes.

3. Which of the following stages of meiosis generates genetic diversity?

   (A) prophase I
   (B) prophase II
   (C) anaphase I
   (D) anaphase II

4. Independent assortment of chromosomes occurs during which stage of meiosis?

   (A) metaphase I
   (B) metaphase II

(C) telophase I
(D) telophase II

5. Which of the following is a correct statement about meiosis?

(A) DNA replication occurs once, and there is one round of cell division.
(B) DNA replication occurs twice, and there is one round of cell division.
(C) DNA replication occurs once, and there are two rounds of cell division.
(D) DNA replication occurs twice, and there are two rounds of cell division.

6. How does the frequency of recombination events between genes that are close together on the same chromosome compare to the frequency of recombination events between genes that are far apart on the same chromosome?

(A) Genes that are close together on the same chromosome will recombine less frequently than genes that are far apart.
(B) Genes that are close together on the same chromosome will recombine more frequently than genes that are far apart.
(C) Genes that are close together on the same chromosome will recombine at the same rate as genes that are far apart.
(D) Genes that are on the same chromosome never have recombination events between them.

7. Which of the following statements correctly describes a difference between mitosis and meiosis?

(A) Mitosis produces four daughter cells, whereas meiosis produces two daughter cells.
(B) Mitosis produces genetically different cells, whereas meiosis produces genetically identical cells.

(C) Mitosis produces somatic cells, whereas meiosis produces gametes.

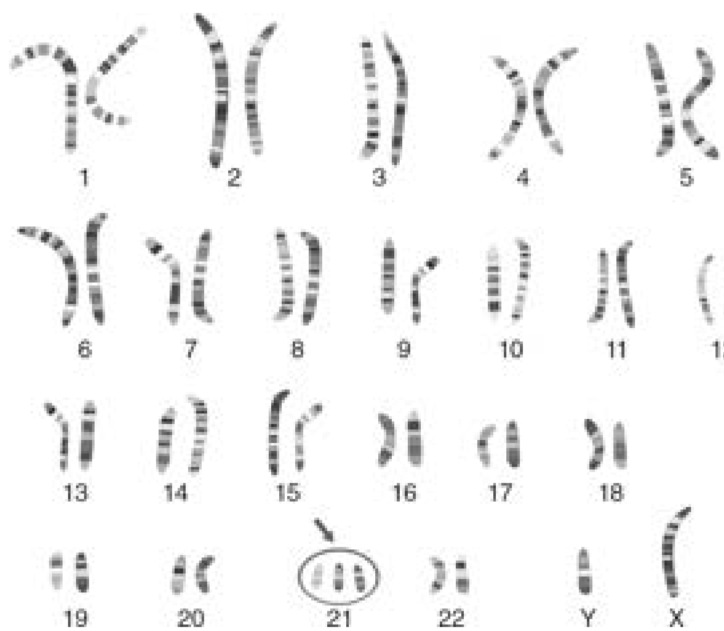
(D) Mitosis produces haploid cells, whereas meiosis produces diploid cells.

8. Aneuploidies can result from errors during which stage of meiosis?

(A) prophase I
(B) metaphase I
(C) anaphase I
(D) telophase I

Questions 9 and 10

The following figure is a karyotype, a picture that shows the chromosomes found in a somatic human cell.



9. Which of the following best describes the condition shown in the circle?

(A) trisomy
(B) haploidy

(C) monosomy

(D) diploidy

10. Which of the following was the most likely cause of the condition shown in the circle?

(A) translocation

(B) independent assortment

(C) nondisjunction

(D) genetic recombination

Short Free-Response

11. Genes *A, B*, and *C* are on the same chromosome. The frequencies of genetic recombination events between the genes is shown in the following table.

Genes	Recombination Frequency
AB	45%
BC	15%
AC	30%

(a) Using this data and the following template, **construct** a genetic map of these three genes.

(b) **Explain** your placement of the three genes on the genetic map from part (a).

(c) A new gene, *D*, is discovered on the same chromosome. *A* and *D* have a recombination frequency of 10%. *B* and *D* have a recombination frequency of 35%. On your genetic map from part (a), **draw** an additional line to represent the relative location of gene *D* on the chromosome.

(d) A different chromosome in the organism has genes, *M, N, O*, and *P*. One copy has the alleles *MNOP*. The other copy of the chromosome has the alleles *mnop*. If genetic recombination occurred between genes *N* and *O*, **explain** the two possible gametes that would be produced by this crossing-over event.

12. An organism has a diploid number of six chromosomes.

(a) **Determine** the number of chromosomes in each of the four cells that would be produced upon the completion of meiosis II.

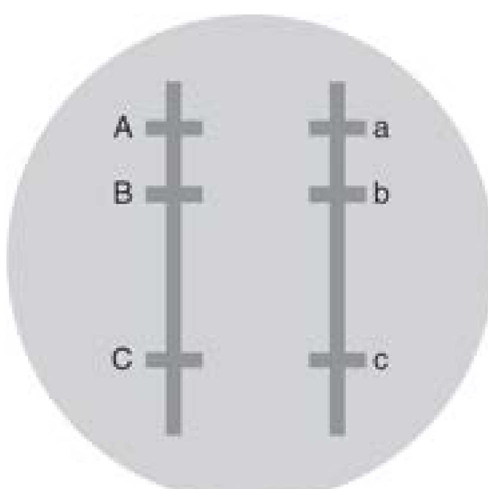
(b) Based on your answer to part (a), **explain** why the cells would each have that number of chromosomes at the end of meiosis II.

(c) A nondisjunction event occurred during anaphase II. **Predict** the number of chromosomes that would be found in each of the four cells after this nondisjunction event.

(d) **Justify** your prediction from part (c).

Long Free-Response

13. An organism has the two chromosomes shown in the following figure.



A student claims that exposure to UV light prior to meiosis will increase the frequency of genetic recombination during meiosis. Gamete-producing cells from this organism are placed into two groups. One group is not exposed to UV light, and the other group is exposed to UV light prior to undergoing meiosis. The gametes produced at the end of meiosis and the frequencies of those gametes are shown in the following table.

Gamete	Frequency of Gametes in Cells Not Exposed to UV Light	Frequency of Gametes in Cells Exposed to UV Light
ABC	48%	35%
ABc	2%	15%
abC	2%	15%
abc	48%	35%

(a) **Identify** and **explain** the stage of meiosis during which genetic recombination occurs.

(b) **Identify** the independent variable and the dependent variable in this experiment.

(c) Using the data, provide reasoning to **support the student's claim**.

(d) The experiment is repeated with increased exposure to UV light (for the cells that were exposed to UV light). **Predict** how this change will affect the recombination frequencies. **Justify** your prediction.

Answer Explanations

Multiple-Choice

1. **(D)** Meiosis produces four genetically different haploid cells. Choice (A) is incorrect because it describes the products of mitosis. Choice (B) is incorrect because meiosis produces four cells, not two cells, and those four cells are haploid, not diploid. Choice (C) is incorrect because meiosis produces genetically different cells, not genetically identical cells.

2. **(B)** Somatic (body) cells have the diploid number of chromosomes (which is 28, based on the question), and gametes have the haploid number of chromosomes (which, in this case, is 14). Choice (A) is incorrect because it assigns the haploid number of chromosomes to the somatic cells and the diploid number of chromosomes to the gametic cells. Choices (C) and (D) are both incorrect because somatic cells and gametes have different numbers of chromosomes, not the same number of chromosomes.

3. **(A)** Genetic recombination (crossing-over), which generates genetic diversity, occurs during prophase I. Choices (B), (C), and (D) are incorrect because genetic diversity is not generated in prophase II, anaphase I, or anaphase II. (Note that genetic diversity is generated in metaphase I of meiosis, but that is not one of the choices in this question.)

4. **(A)** Pairs of homologous chromosomes assort independently during metaphase I. Choice (B) is incorrect because individual chromosomes line up on the metaphase plate in metaphase II, and no independent assortment of chromosomes occurs. In both telophase I and telophase II, new nuclear membranes are formed. No assortment of chromosomes occurs during those stages, so choices (C) and (D) are incorrect.

5. **(C)** DNA is replicated once before meiosis I starts, and meiosis is comprised of two rounds of cell division. Choice (A) is incorrect because it describes what happens during mitosis, not meiosis. Choice (B) is incorrect because DNA replication only occurs once in meiosis,

and there are two rounds of cell division in meiosis. Choice (D) is incorrect because DNA replication only occurs once in meiosis.

6. **(A)** Genes that are close together on the same chromosome have fewer opportunities for recombination than genes that are farther apart on the same chromosome. Thus, recombination events between genes that are close together on the same chromosome occur less frequently than recombination events between genes that are farther apart on the same chromosome. Choice (B) is the opposite of the correct answer. The distance between genes does affect the frequency of recombination events, so choice (C) cannot be the answer. Typically, recombination events do occur between genes on the same chromosome, so choice (D) is not correct.

7. **(C)** Mitosis produces somatic (body) cells, whereas meiosis produces gametes. Choice (A) is incorrect because mitosis produces two cells whereas meiosis produces four cells. Mitosis produces genetically identical cells, whereas meiosis produces genetically different cells, so choice (B) is incorrect. Haploid gametes are produced by meiosis, whereas diploid cells are produced by mitosis. So choice (D) is incorrect.

8. **(C)** Pairs of homologous chromosomes separate during anaphase I and ultimately end up in different cells at the end of telophase I. If a pair of homologous chromosomes did not separate in anaphase I, one of the two cells at the end of telophase I would have both members of the pair of homologous chromosomes and the other cell would have neither member of the pair of homologous chromosomes. The resulting gametes would have an incorrect number of chromosomes (either one too many or one too few), which results in an aneuploidy. Choices (A), (B), and (D) are incorrect because chromosomes do not separate in those stages, so errors in those stages would not result in an aneuploidy.

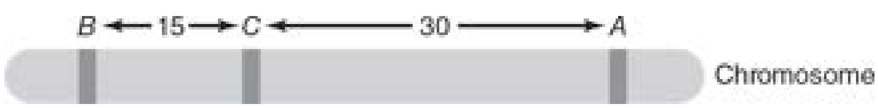
9. **(A)** Trisomy describes the condition where there are three copies of a given chromosome when there would typically be two copies. Choice (B) is incorrect because haploidy describes the conditions where there is only one copy of each chromosome. Monosomy is when there is one

copy of a given chromosome, so choice (C) is incorrect. Choice (D) is incorrect because diploidy describes the conditions where there are two copies of each chromosome.

10. **(C)** Nondisjunction is when two homologous chromosomes do not separate during meiosis. If a nondisjunction event occurs, the resulting gamete will have an extra copy of that chromosome. If that gamete is fertilized by a haploid gamete, the resulting cell will have three copies of the chromosome, as shown in the figure. Translocation describes mutations that are the result of genetic recombination between nonhomologous chromosomes, so choice (A) is incorrect. Choice (B) is incorrect because independent assortment is the independent alignment of pairs of homologous chromosomes in metaphase I; this does not affect the number of chromosomes found in a cell. Choice (D) is incorrect because genetic recombination describes the exchange of genetic material between chromosomes; this would not result in the presence of three copies of a chromosome.

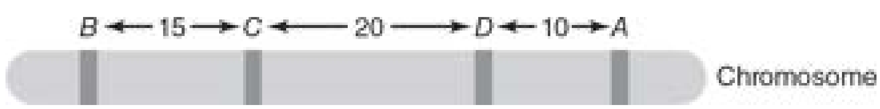
Short Free-Response

11. (a)



(b) *B* and *C* have the lowest recombination frequency at 15%, so they must be the closest together of the three genes. *A* and *C* have a recombination frequency of 30%, and *A* and *B* have a recombination frequency of 45%, so *A* must be closer to *C* than *A* is to *B*. So the correct placement of the three genes on the chromosome must be as shown in part (a).

(c)



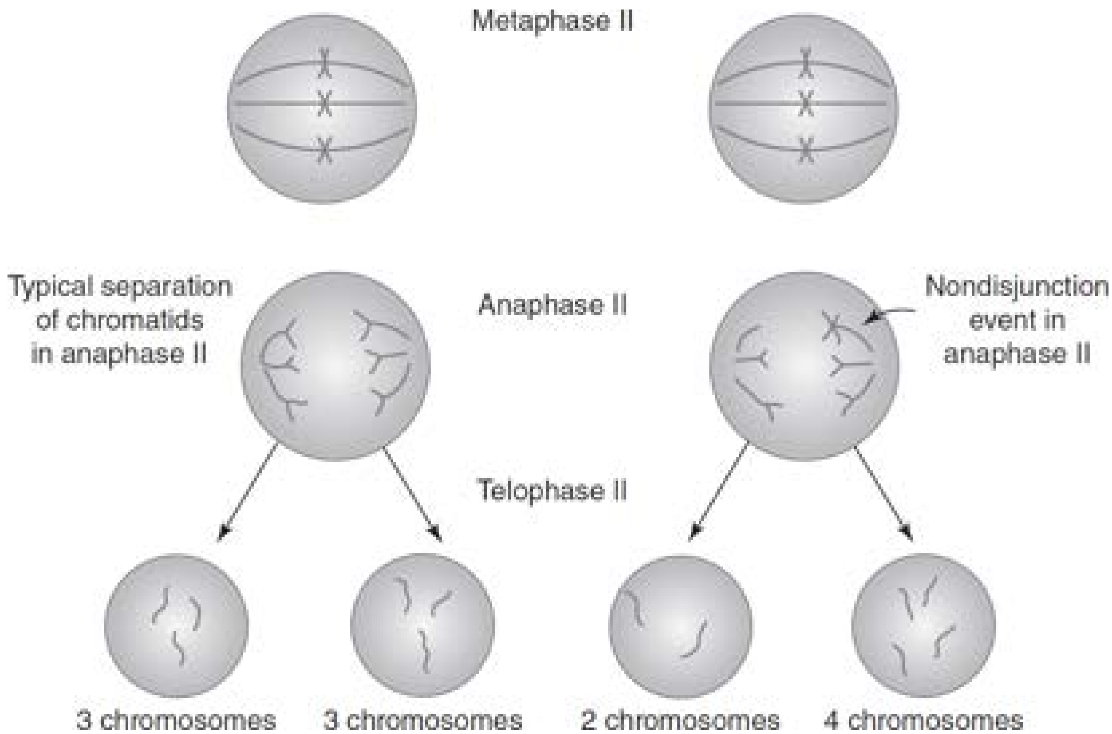
(d) If a crossover event occurred between genes *N* and *O* as shown in the following figure, the resulting gametes would have the genotypes *MNop* and *mnOP*.

12. (a) At the end of meiosis II, one would expect to find three chromosomes in each gamete.

(b) Meiosis starts with a diploid cell and produces four haploid gametes. So if the original cell had a diploid number of six, the gametes would typically each have a haploid number of three.

(c) Two cells would have three chromosomes each, one cell would have four chromosomes, and one cell would have two chromosomes.

(d) If the nondisjunction event occurred during anaphase II, the result would be as shown in the following figure because the sister chromatids of the chromosome would not separate. Both chromatids would end up in the same cell instead of in two separate cells. This would result in an extra chromosome in the cell that received both chromatids and a missing chromosome in the cell that did not receive either chromatid.



Long Free-Response

13. (a) Genetic recombination occurs during the prophase I stage of meiosis. During prophase I, homologous chromosomes synapse (pair up) to form tetrads. These tetrads can then exchange genetic information.

(b) The independent variable is exposure to UV light. The dependent variable is the percentage of recombinant gametes produced.

(c) Cells that were exposed to UV light prior to undergoing meiosis produced more recombinant gametes. So this supports the student's claim that exposure to UV light prior to meiosis would increase the frequency of genetic recombination.

(d) More exposure to UV light would probably produce even more recombinant gametes. Since the initial exposure to UV light resulted in more recombinant gametes (than in those cells that were not exposed to UV light), more exposure to UV light would further increase the number of recombinant gametes.