Chapter 7

Cell Cycle

Review

Cell division consists of two phases, **nuclear division** followed by **cytokinesis.** Nuclear division divides the genetic material in the nucleus, while cytokinesis divides the cytoplasm. There are two kinds of nuclear division—**mitosis** and **meiosis.** Mitosis divides the nucleus so that both daughter cells are genetically identical. In contrast, meiosis is a reduction division, producing genetically variable daughter cells that contain half the genetic information of the parent cell.

The first step in either mitosis or meiosis begins with the condensation of the genetic material, **chromatin,** into tightly coiled bodies, the **chromosomes.** Each chromosome is made of two identical halves called **sister chromatids** joined at the **centromere** (Figure 7-1). Each chromatid consists of a single, tightly coiled molecule of DNA, the genetic material of the cell. In diploid cells, there are two copies of every chromosome, forming a pair, called homologous chromosomes. In a homologous pair of chromosomes, one homologue originated from the maternal parent, the other from the paternal parent. Humans have 46 chromosomes, 23 homologous pairs, consisting of a total of 92 chromatids.

The **cell cycle** describes the sequence of events that occurs during the life of most eukaryotic cells (Figure 7-2). During **interphase,** the period during which the cell is *not* dividing, the chromatin is enclosed within a clearly defined nuclear envelope. Within the nucleus, one or more **nucleoli** are visible. Outside the nucleus, two **microtubule organizing centers (MTOCs)** lie adjacent to one another. In animals, the MTOCs are the centrosomes, and each contains a pair of **centrioles.** When cell division begins, these features change, as described in the "Mitosis and Cytokinesis" section that follows.

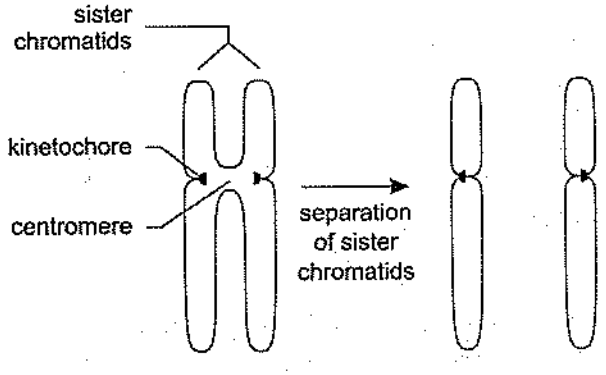


Figure 7-1

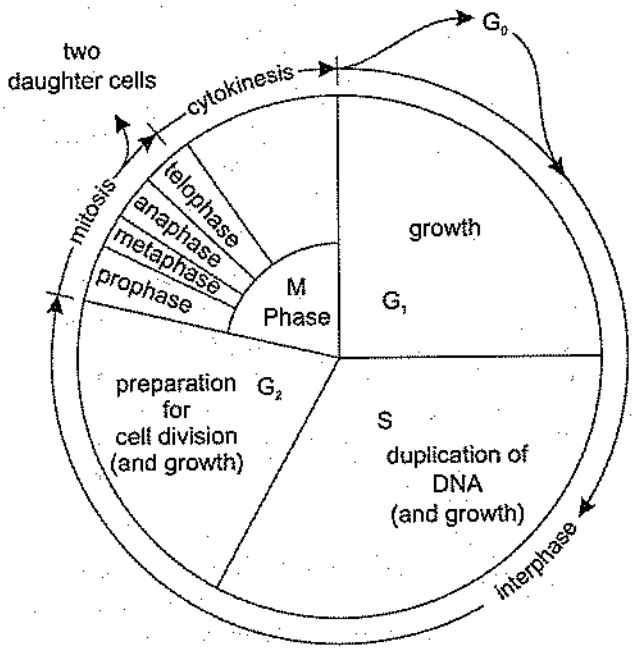


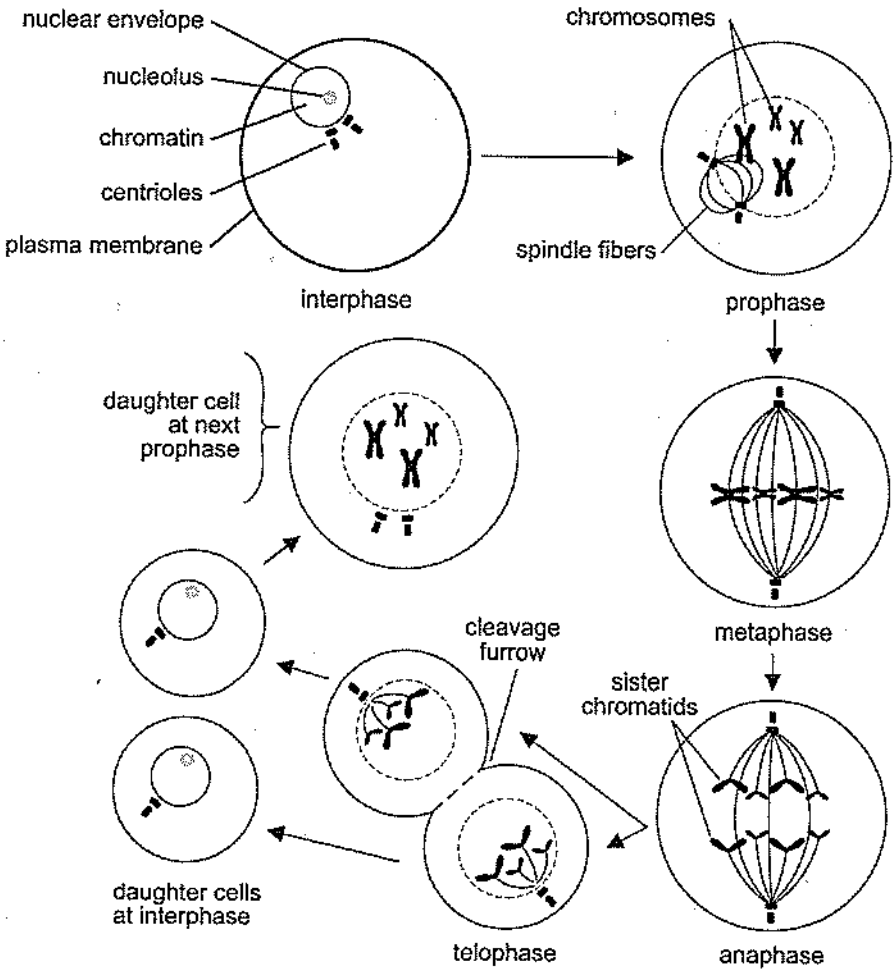
Figure 7-2

Mitosis and Cytokinesis

Mitosis is the division of the nucleus to form two nuclei, and **cytokinesis** is the division of the cytoplasm to form two new cells, each with one nucleus. Together, they occur during the **M phase** of the cell cycle.

Mitosis

There are four phases in mitosis (adjective, **mitotic**): **prophase, metaphase, anaphase,** and **telophase** (Figure 7-3). Cytokinesis begins during telophase. A description of each mitotic stage follows. A single word in parentheses highlights the main feature of each phase.



Mitosis in an Animal Cell

Figure 7-3

1. In **prophase (condensation)**, three activities occur simultaneously. First, the nucleoli disappear and the chromatin condenses into chromosomes. Second, the nuclear envelope breaks down. Third, the **mitotic spindle** is assembled. The development of the mitotic spindle begins as the MTOCs move apart to opposite ends (or poles) of the nucleus. As they move apart, microtubules develop from each MTOC, increasing in length by the addition of tubulin units to the microtubule ends away from the MTOC. Microtubules from each MTOC connect to a specialized region in the centromere called a **kinetochore.** Microtubules tug on the kinetochore, moving the chromosomes back and forth, toward one pole, then the other. In addition to these microtubules, the completed spindle also includes other microtubules from each MTOC that overlap at the center of the spindle and do not attach to the chromosomes.

2. **Metaphase (alignment)** begins when the chromosomes are aligned across the **metaphase plate,** a plane lying between the two poles of the spindle. Metaphase ends when the microtubules, still attached to the kinetochores, pull each chromosome apart into two chromatids. Each chromatid is complete with a centromere and a kinetochore. Once separated from its sister chromatid, each chromatid is called a chromosome. (To count the number of chromosomes at any one time, count the number of centromeres.)
3. **Anaphase (separation)** begins after the chromosomes are separated into chromatids. During anaphase, the microtubules connected to the chromatids (now chromosomes) shorten, effectively pulling the chromosomes to opposite poles. The microtubules shorten as tubulin units are uncoupled at their chromosome ends. Overlapping microtubules originating from opposite MTOCs, but not attached to chromosomes, interact to push the poles farther apart. At the end of anaphase, each pole has a complete set of chromosomes, the same number of chromosomes as the original cell. (Since they consist of only one chromatid, each chromosome contains only a single copy of the DNA molecule.)
4. **Telophase (restoration)** concludes the nuclear division. During this phase, a nuclear envelope is restored around each pole, forming two nuclei. The chromosomes within each of these nuclei disperse into chromatin, and the nucleoli reappear.

Cytokinesis

Whereas mitosis divides the nucleus into two daughter nuclei, cytokinesis divides the cytoplasm to form two cells. Cytokinesis differs in plants and animals by the formation of two kinds of structures, as follows:

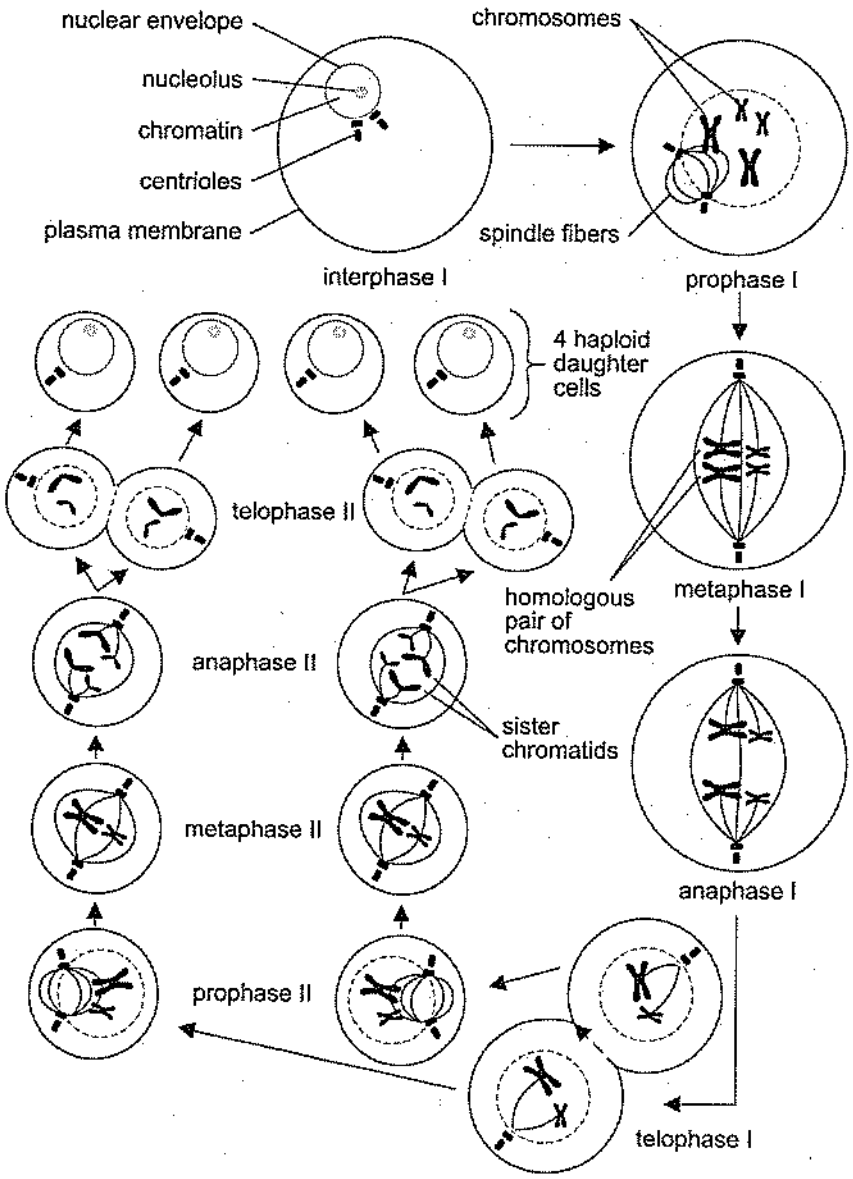
- **Cell plate.** In plants, vesicles originating from Golgi bodies migrate to the plane between the two newly forming nuclei. The membranes of the vesicles fuse to form two new plasma membranes, and the contents of the vesicles form a **cell plate,** which develops into the new cell wall.
- **Cleavage furrow.** In animals, actin filaments (microfilaments) form a ring inside the plasma membrane between the two newly forming nuclei. As the actin filaments shorten, they act like purse strings to pull the plasma membrane into the center, dividing the cell into two daughter cells. The groove that forms as the purse strings are tightened is called a **cleavage furrow.**

When mitosis and cytokinesis are completed and interphase begins, the cell begins a period of growth. This growth period is divided into three phases, designated **G_1, S,** and **G_2,** to distinguish special activities that occur. Although you can associate the labels G_1 and G_2 with growth and S with synthesis, it is important to recognize that growth takes place during all three phases. The S phase marks the time during which the second DNA molecule for each chromosome is synthesized. As a result of this DNA replication, each chromosome that appears at the beginning of the next mitotic division will appear as two sister chromatids. During the G_2 period of growth, materials for the next mitotic division are prepared. The time span through mitosis and cytokinesis (M phase), through G_1, S, and G_2 **(interphase),** is the cell cycle (Figure 7-2).

A diploid cell is a cell with two copies of every chromosome (designated by $2n$). A cell that begins mitosis in the diploid state will end mitosis with daughter cells still in the diploid state, each with two identical copies of every chromosome. However, each of these chromosomes will consist of only one chromatid (one DNA molecule). During the S phase of interphase, the second DNA molecule is replicated from the first, so when the next mitotic division begins, each chromosome will, again, consist of two chromatids.

Meiosis

Meiosis (adjective, **meiotic**) is very similar to mitosis. Because of the similarity, however, the two processes are easily confused. The major distinction is that meiosis consists of two groups of divisions: meiosis I and meiosis II (Figure 7-4). In meiosis I, homologous chromosomes pair at the metaphase plate, and then the homologues migrate to opposite poles. In meiosis II, chromosomes spread across the metaphase plate and sister chromatids separate and migrate to opposite poles. Thus, meiosis II is analogous to mitosis. A description of each meiotic stage follows. A single word in parentheses highlights the main feature of each phase.



Meiosis in an Animal Cell

Figure 7-4

1. **Prophase I (condensation)** begins like prophase of mitosis. The nucleolus disappears, chromatin condenses into chromosomes, the nuclear envelope breaks down, and the spindle apparatus develops. Unlike mitosis, however, once the chromosomes are condensed, *homologous chromosomes pair with each other,* a process called **synapsis.** During synapsis, corresponding regions along *non*sister chromatids form close associations called **chiasmata** (singular, **chiasma**). Chiasmata are sites where genetic material is exchanged between nonsister homologous chromatids, a process called **crossing over.**
2. At **metaphase I (alignment),** homologous pairs of chromosomes are spread across the metaphase plate. Microtubules extending from one pole are attached to the kinetochore of one member of each homologous pair. Microtubules from the other pole are connected to the second member of each homologous pair.
3. **Anaphase I (separation)** begins when homologues uncouple as they are pulled to opposite poles.

4. In **telophase I (restoration),** the chromosomes have reached their respective poles, and a nuclear membrane develops around them. Note that each pole will form a new nucleus that will have half the number of chromosomes, but each chromosome will contain two chromatids. Since daughter nuclei will have half the number of chromosomes, cells that they eventually form will be **haploid.**

   Beginning in telophase I, the cells of many species begin cytokinesis and form cleavage furrows or cell plates. In other species, cytokinesis is delayed until after meiosis II. Also, a short interphase II may begin. In any case, no replication of chromosomes occurs during this period. Instead, part II of meiosis begins in both daughter nuclei.
5. In **prophase II (condensation),** the nuclear envelope disappears and the spindle develops. There are no chiasmata and no crossing over of genetic material as in prophase I.
6. In **metaphase II (alignment),** the chromosomes align singly on the metaphase plate (not in pairs, as in metaphase I). Single alignment of chromosomes is exactly what happens in *mitosis* except here, in meiosis, there is only half the number of chromosomes.
7. **Anaphase II (separation)** begins as each chromosome is pulled apart into two chromatids by the microtubules of the spindle apparatus. The chromatids (now chromosomes) migrate to their respective poles. Again, this is exactly what happens in mitosis, except that now there is only half the number of chromosomes.
8. In **telophase II (restoration),** the nuclear envelope reappears at each pole and cytokinesis occurs. The end result of meiosis is four haploid cells (chromosome makeup of each daughter cell designated by *n*). Each cell contains half the number of chromosomes, and each chromosome consists of only one chromatid.

Mitosis versus Meiosis

Comparing mitosis and meiosis (Table 7-1), you will find that mitosis ends with two *diploid* daughter cells, each with a complete set of chromosomes. True, each chromosome is composed of only one chromatid, but the second chromatid is regenerated during the S phase of interphase. Mitosis, then, merely duplicates cells; the two daughter cells are essentially clones of the original cell. As such, mitosis occurs during growth and development of multicellular organisms and for repair (replacement) of existing cells. Mitosis is also responsible for asexual reproduction, common among plants and single-celled eukaryotes. Mitosis occurs in **somatic** cells, all body cells except those that produce eggs and sperm (or pollen).

In contrast, meiosis ends with four *haploid* daughter cells, each with half the number of chromosomes (one chromosome from every homologous pair). In order for one of these haploid cells to produce a "normal" cell with the full set of chromosomes, it must first combine with a second haploid cell to create a diploid cell. In other words, meiosis produces **gametes**, that is, eggs and sperm (or pollen), for sexual reproduction. The fusing of an egg and a sperm, **fertilization** (or **syngamy**), gives rise to a diploid cell, the zygote. The single-celled **zygote** then divides by mitosis to produce a multicellular organism. Note that one copy of each chromosome in the zygote originates from one parent, and the second copy originates from the other parent. Thus, a pair of homologous chromosomes in the diploid zygote represents both maternal and paternal heritage.

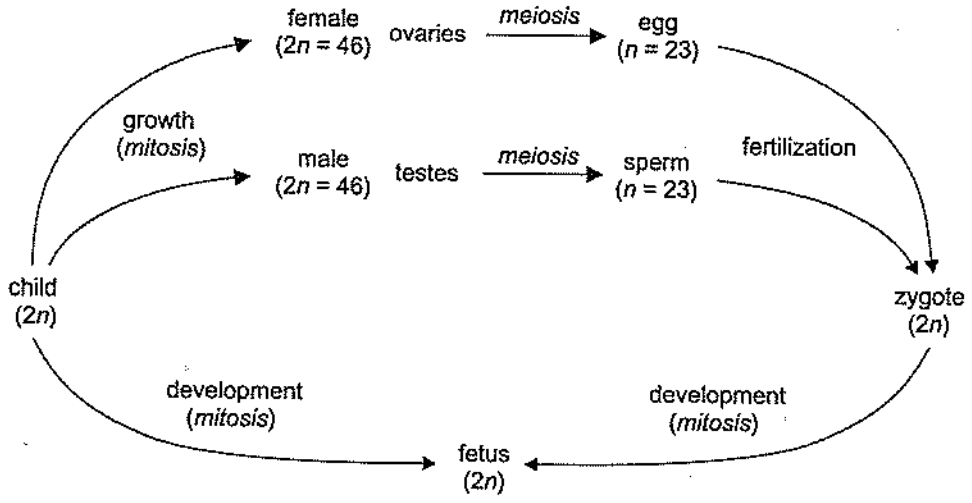
Table 7-1

Characteristics in a Human Cell	Mitosis	Meiosis I	Meiosis II
Chromosome number in a parent cell before division begins	46	46	
Chromatid number in a parent cell before division begins	92	92	
Crossing over at prophase	No	Yes	No

continued

Characteristics in a Human Cell	Mitosis	Meiosis I	Meiosis II
Chromosome arrangement on metaphase plate	Chromosomes line up	Homologues pair	Chromosomes line up
Number of daughter cells at end of division	2	2	4
Chromosome notation for daughter cells	$2n$	n	n
Number of chromosomes in each daughter nucleus	46	23	23
Number of chromatids in each daughter nucleus before replication	46	46	23
Genome notation for daughter cells	Diploid	Haploid	Haploid
Purpose of division	Cell replacement, organism growth, asexual reproduction	Sexual reproduction	
Genetics of daughter cells	Genetically identical (clones)	Genetically variable	
Type of cells where division occurs	Somatic cells	Reproductive cells (ovaries, testes, anthers)	
Type of cells produced	Somatic cells	Gametes: eggs, sperm, pollen	

The **life cycle** of a human illustrates the production of gametes by meiosis and subsequent growth by mitosis (Figure 7-5). Note that the number of chromosomes in diploid and haploid cells is indicated by $2n$ and n, respectively. Human cells (except gametes) contain 46 chromosomes (23 homologous pairs). Thus, $2n = 46$. For human gametes, $n = 23$. In humans, gametes are produced in the reproductive organs—the ovaries and the testes.



The Human Life Cycle

Figure 7-5

Genetic Variation

In mitosis, barring an error in DNA replication (mutation), every daughter cell is exactly like the parent cell. Meiosis and sexual reproduction, however, result in a reassortment of the genetic material. This reassortment, called **genetic recombination,** originates from three events during the reproductive cycle:

1. **Crossing over.** During prophase I, nonsister chromatids of homologous chromosomes exchange pieces of genetic material. As a result, each homologue no longer entirely represents a single parent.
2. **Independent assortment of homologues.** During metaphase I, the homologues of each pair of homologous chromosomes separate and go to opposite poles. Which chromosome goes to which pole depends upon the orientation of a chromosome pair at the metaphase plate. This orientation and subsequent separation is random for each homologous pair. For some chromosome pairs, the chromosome that is mostly maternal may go to one pole, but for another pair, the maternal chromosome may go to the other pole.
3. **Joining of gametes.** Because sexual reproduction requires the gametes of two individuals, new and variable combinations are created. Further variation is introduced because which sperm fertilizes which egg is to a large degree a random event. In many cases, however, this event may be affected by the genetic composition of a gamete. For example, some sperm may be faster swimmers and have a better chance of fertilizing the egg.

Regulation of the Cell Cycle

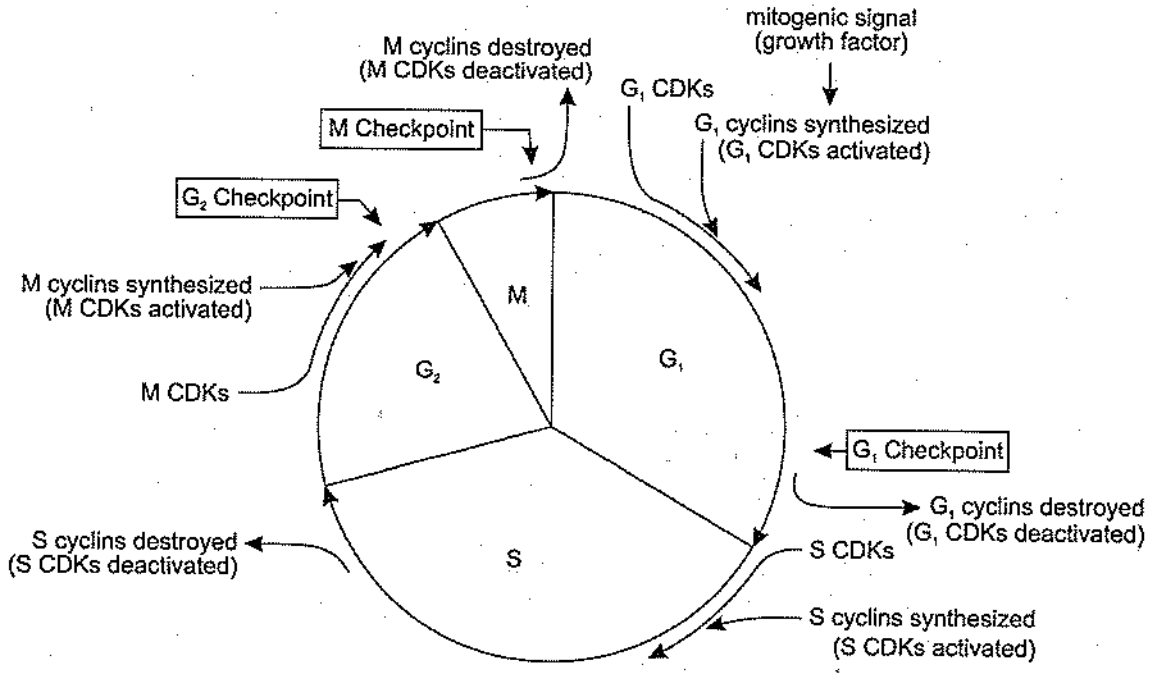
Various factors determine whether and when a cell divides. Two *functional* limitations for cell size limit growth or influence the start of a new cell division, as follows:

1. **Surface-to-volume ratio (S/V).** When a cell grows, the volume of a cell increases faster than the surface area of the plasma membrane enclosing it. This is because volume increases by the cube of the radius (volume of a sphere $= \frac{4}{3}\pi r^3$, where r is the radius), whereas the surface area increases by only the square of the radius (surface area $= 4\pi r^2$). When S/V is large, the surface area is large relative to the volume. Under these conditions, the cell can efficiently react with the outside environment. For example, adequate amounts of oxygen (for respiration) can diffuse into the cell, and waste products can be rapidly eliminated. When S/V is small, the surface area is small compared to the volume. When this occurs, the surface area might be unable to exchange enough substances with the outside environment to service the large volume of the cell. At this point, cell growth stops or cell division begins.
2. **Genome-to-volume ratio (G/V).** The genetic material (chromosomes) in the nucleus, collectively called its **genome,** controls the cell by producing substances that make enzymes and other biosynthetic substances. These substances, in turn, regulate cellular activities. The capacity of the genome to do this is limited by its finite amount of genetic material. As the cell grows, its volume increases, but its genome size remains constant. As the G/V decreases, the cell's size exceeds the ability of its genome to produce sufficient amounts of materials for regulating cellular activities.

At the molecular level, the cell cycle is strictly controlled by various signal molecules within the cell. These signals respond to *internal* factors, ensuring that the necessary steps in the cell cycle have been accurately completed before going on to the next step in the cell cycle.

1. **Checkpoints.** At specific points during the cell cycle, the cell evaluates internal and external conditions to determine whether to continue through the cell cycle. The three checkpoints are as follows (Figure 7-6):
   - The G_1 **checkpoint** occurs near the end of the G_1 phase. Here, the quality of the DNA is evaluated; if DNA damage is detected, DNA repair is attempted. If that fails, **apoptosis,** a program for self-destruction, ensues. If nutrients or growth factors are absent, the cell proceeds no further through the cell cycle, remaining in an extended G_1 phase until conditions are appropriate. Some cells, like nerve or muscle cells, are genetically programmed not to divide, and they remain in a G_0 **phase,** rarely dividing after they have matured. Liver cells, on the other hand, can leave the G_0 phase and return to dividing if they need to replace injured liver tissue.

- The **G_2 checkpoint,** occurring at the end of the G_2 phase of the cell cycle, evaluates the accuracy of DNA replication and signals whether to begin mitosis. If DNA damage is detected, DNA repair is attempted. If repair is unsuccessful, apoptosis ensues.
- The **M checkpoint,** occurring during metaphase, ensures that microtubules are properly attached to all kinetochores at the metaphase plate before division continues with anaphase.



Regulation of the Cell Cycle
Figure 7-6

2. **Cyclin-dependent kinases (CDKs).** CDKs are proteins responsible for advancing the cell past the checkpoints and through the cell cycle. CDKs have the following attributes:
   - **CDKs are kinases.** Kinases are enzymes that phosphorylate other proteins. Once phosphorylated, the protein is energized and ready to act. Proteins can be *inactivated* by dephosphorylation or by destruction by other enzymes.
   - **CDKs are activated by cyclins.** Cyclins are proteins that attach to CDKs, altering their conformation and readying them for activation. Complete activation requires phosphorylation. Without a cyclin attached, a CDK is inactive (that's why it's described as "cyclin dependent").
   - **Mitosis-promoting factor (or maturation-promoting factor) (MPF)** is a cyclin-CDK complex that advances the cell cycle through the G_2 checkpoint. Each checkpoint has its own combination of a specific CDK and a specific cyclin that advances the cell cycle through the checkpoint.

Concentrations of different cyclins vary ("cycle") during the cell cycle with a regular pattern. As the cell cycle approaches each checkpoint, a specific cyclin combines with a specific CDK (Figure 7-6). The conformation change that results unblocks an active site on the CDK, readying it for activation. If checkpoint conditions are met, the CDK is activated, often by phosphorylation, and the activated cyclin-CDK complex initiates activity that advances the cell cycle through the checkpoint. Once through the cycle phase, the cyclins are destroyed, and new cyclins, specific for the next checkpoint, begin to accumulate.

Various *external* factors also influence the cell cycle:

1. **Growth factors.** The plasma membranes of cells have receptors for growth factors that stimulate a cell to divide. For example, platelets are cell fragments that circulate in the blood and contribute to the clotting mechanism. When platelets encounter damaged tissue, they release **platelet-derived growth factor (PDGF),** which binds to the plasma membrane of fibroblasts (a connective tissue) and stimulates its cell division. The new fibroblasts contribute to the healing of damaged tissue. More than 50 different growth factors are known.
2. **Density-dependent inhibition.** Many cells stop dividing when the surrounding cell density reaches a certain maximum.
3. **Anchorage dependence.** Most cells only divide when they are attached to an external surface, such as the flat surface of a neighboring cell (or the side of a culture dish).

Cancer is characterized by uncontrolled cell growth and division. **Transformed** cells, cells that have become cancerous, proliferate without regard to cell cycle checkpoints, density-dependent inhibition, anchorage dependence, and other regulatory mechanisms. Thus, cancer is a disease of the cell cycle.

Review Questions

Multiple-Choice Questions

The questions that follow provide a review of the material presented in this chapter. Use them to evaluate how well you understand the terms, concepts, and processes presented. Actual AP multiple-choice questions are often more general, covering a broad range of concepts, and often more lengthy. For multiple-choice questions typical of the exam, take the two practice exams in this book.

Directions: Each of the following questions or statements is followed by four possible answers or sentence completions. Choose the one best answer or sentence completion.

1. If a cell has 46 chromosomes at the beginning of mitosis, then at the separation phase (anaphase) there would be a total of

   A. 23 chromatids
   B. 46 chromosomes
   C. 46 chromatids
   D. 92 chromosomes

2. If a cell has 46 chromosomes at the beginning of the first meiotic division, then at the separation phase of the first meiotic division (anaphase I) there would be a total of

   A. 23 chromosomes
   B. 46 chromosomes
   C. 46 chromatids
   D. 92 chromosomes

3. All of the following statements are true EXCEPT:

   A. Spindle fibers are composed largely of microtubules.
   B. Centrioles consist of nine triplets of microtubules arranged in a circle.
   C. All eukaryotic cells have centrioles.
   D. All eukaryotic cells have a spindle apparatus.

Questions 4–7 refer to a mitotically dividing cell and to the lettered answer choices below. Each answer may be used once, more than once, or not at all.

A. anaphase (separation)
B. telophase (restoration)
C. prophase (condensation)
D. interphase (nondividing)

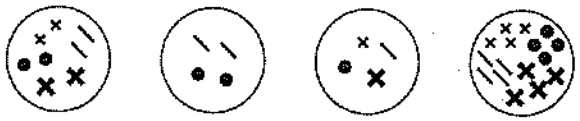
4. Cytokinesis begins.

5. Chromosomes begin migrating to opposite poles.

6. MTOCs migrate to opposite poles.

7. Chromosomes replicate.

Questions 8–9 refer to the following figures. Figure A represents a normal diploid cell with 2n = 8. Each of the four symbols inside the cell represents a unique chromosome.



A. B. C. D.

8. a zygote

9. a gamete

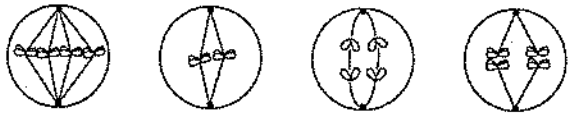
10. Crossing over occurs during which of the following prophase (condensation) events?

A. prophase of mitosis
B. prophase I of meiosis
C. prophase II of meiosis
D. prophase I and II of meiosis

11. In typical cell divisions, all of the following contribute to genetic variation EXCEPT:

A. anaphase (separation) of mitosis
B. anaphase (separation) of meiosis I
C. fertilization
D. crossing over

Questions 12–16 refer to the cell illustrations below. The normal diploid number for the cells illustrated is four chromosomes. Each answer may be used once, more than once, or not at all.



A. B. C. D.

12. anaphase (separation) II

13. metaphase (alignment) II

14. metaphase (alignment) of mitosis

15. metaphase (alignment) I

Free-Response Questions

The AP exam has long and short free-response questions. The long questions have considerable descriptive information that may include tables, graphs, or figures. The short questions are brief but may also include figures. Both kinds of questions have four parts and generally require that you bring together concepts from multiple areas of biology.

The questions that follow are designed to further your understanding of the concepts presented in this chapter. Unlike the free-response questions on the exam, they are narrowly focused on the material in this chapter. For free-response questions typical of the exam, take the two practice exams in this book.

Directions: The best way to prepare for the AP exam is to write out your answers as if you were taking the exam. Use complete sentences and do *not* use outline form or bullets. You may use diagrams to supplement your answers, but be sure to describe the importance or relevance of your diagrams.

1. Many of the activities that occur during mitosis and meiosis are similar. Describe one stage of meiosis that is distinctively different from mitosis.

2. Genetic variation is a product of meiosis. Describe how genetic variation is created by meiosis.

3. The cell cycle is strictly regulated by various processes. Describe what goes wrong when a cell is overtaken by cancer.

4. Describe the process of cell division in plants and animals, giving specific attention to the following:

- **a.** the stages of mitosis, cytokinesis, and other phases of the cell cycle (do not include meiosis)
- **b.** factors that induce cells to divide
- **c.** factors that might contribute to abnormal cell divisions, such as cancer

5. Describe meiosis in animal and plant cells, giving specific attention to the following:

- **a.** the stages of meiosis
- **b.** the function of meiotic daughter cells and the organs where meiosis takes place
- **c.** contributions to genetic variation

Answers and Explanations

Multiple-Choice Questions

1. D. At metaphase, there are 46 chromosomes with 2 chromatids each, for a total of 92 chromatids. Metaphase ends and anaphase begins when the 2 chromatids of each chromosome separate. Once separated, these 92 chromatids become 92 chromosomes because each chromatid is now considered a complete chromosome, since it consists of a complete DNA molecule. (To count the number of chromosomes at any point during the cell cycle, count the centromeres.) Thus, there are now 92 chromosomes destined for 2 daughter cells (46 chromosomes per cell). After cytokinesis, each daughter cell contains 46 chromosomes, each consisting of 1 chromatid.

2. **B.** During metaphase I, homologous chromosomes pair at the metaphase plate. One member of each pair migrates to opposite poles during anaphase I. If the cell started with 46 chromosomes, 23 chromosomes move to each pole during anaphase I, so the total is still 46 chromosomes.
3. **C.** Most plants do not have centrioles.
4. **B.** During telophase, cytokinesis begins, chromosomes uncoil into chromatin, and the nuclear membrane and nucleolus reappear.
5. **A.** At metaphase, the chromosomes are arranged on the metaphase plate. The end of metaphase and the beginning of anaphase are defined by the separation of the chromosomes into chromatids (which are now considered chromosomes by themselves). Once anaphase begins, the chromosomes move to one pole or the other.
6. **C.** During prophase, the two MTOCs (and centrioles, if present) migrate to opposite poles as the spindle apparatus develops between them. Also during prophase, the nucleolus and nuclear membrane disappear, and the chromatin condenses into chromosomes.
7. **D.** Chromosomes replicate during the S phase of interphase.
8. **A.** Since the zygote consists of the union of two haploid gametes, the zygote would have the same number of chromosomes as the parent. As in the parent cell, the eight chromosomes would consist of four homologous pairs.
9. **C.** A gamete would possess four chromosomes, half the number of chromosomes as the parent cell. Also, these four chromosomes would consist of one member of each pair of homologous chromosomes. Figure B also has four chromosomes, but it does not present one homologue of each homologous pair.
10. **B.** Homologous chromosomes pair (synapsis) during prophase I and form chiasmata. Exchanges of genetic material occur within chiasmata.
11. **A.** There are generally no events during normal mitosis that would produce genetic differences between the two daughter cells. The daughter cells are clones, genetically identical. In contrast, the independent assortment of homologues during anaphase I, the random union of egg and sperm during fertilization, and crossing over during prophase I all contribute to genetic variation.
12. **C.** At the end of meiosis I, each daughter cell would have two chromosomes, each composed of two chromatids. At metaphase II, these two chromosomes would line up on the metaphase plate. When anaphase II begins, each of the chromosomes would split into two chromatids. One of each of these chromatids (now called chromosomes) would migrate to one or the other pole.
13. **B.** If the cell began with four chromosomes, then after meiosis I, each daughter cell would have two complete chromosomes. At metaphase II, the two chromosomes would align, unpaired, on the metaphase plate.
14. **A.** Only in mitosis would you see four chromosomes spread out, unpaired, on the metaphase plate. If this were metaphase I, the chromosomes would appear in pairs; if it were metaphase II, there would be only two chromosomes.
15. **D.** The pairing of homologous chromosomes occurs only in meiosis and at metaphase I.

Free-Response Questions

1. During chromosome alignment in meiosis I (metaphase I), homologous chromosomes pair on the equatorial plate and subsequently *homologues* separate to opposite poles. In contrast, during the same phase of mitosis, the chromosomes all line up and *chromatids* separate to opposite poles.

2. Crossing over during the condensation phase of meiosis I (prophase I) produces chromosomes with genetic material from both parents. Also, the joining of gametes during sexual reproduction creates genomes in offspring that are unique.

3. When the DNA of a cell is damaged by radiation or chemicals, genes that produce proteins that regulate cell division may have mutated. If, for example, the gene product is a damaged protein that normally monitors the integrity of the DNA, it may not trigger DNA repair and damaged DNA will be passed on to daughter cells. Accumulation of damaged DNA may result in a further breakdown of cell cycle regulation, and the cell line may begin dividing without control, thus becoming cancerous.

4. **a.** Mitosis consists of four phases—prophase, metaphase, anaphase, and telophase. In prophase, the chromatin condenses into chromosomes and the nuclear envelope and nucleolus disappear. As centrioles (or MTOCs, in plants) migrate to opposite poles, microtubules develop between them to form the spindle apparatus. The microtubules attach to the kinetochores in the centromeres of the chromosomes and pull on the chromosomes. At metaphase, the microtubules have pulled the chromosomes so that they are all lined up on the metaphase plate. In anaphase, the sister chromatids of each chromosome are separated and pulled to opposite poles by the microtubules of the spindle apparatus. In telophase, the chromatids are well segregated to opposite poles. Nuclear membranes appear around each pole and chromosomes diffuse into chromatin. Cytokinesis, the dividing of the cytoplasm, begins during telophase. The cell is divided by a cleavage furrow in animals or a cell plate in plants. If the mother cell began with a diploid number of chromosomes, then the two nuclei that form at each pole would also both be diploid, though at this point each chromosome would consist of only a single chromatid.

The entire cell cycle includes both mitosis and interphase. Interphase is a period of growth and is divided into three stages, identified as G_1, S, and G_2. The G_1 phase describes the first period of growth following mitosis. During the S phase, a second DNA molecule (chromatid) is replicated from each chromosome. During the G_2 phase, the cell prepares for mitosis. The M phase describes mitosis and cytokinesis.

b. Various factors induce a cell to divide. Cell size is functionally limited by surface-to-volume and genome-to-volume ratios. As the surface-to-volume ratio becomes progressively smaller as the cell grows, the ability of the plasma membrane to provide a surface large enough to meet the import and export requirements of the cell diminishes. Also, when the cell increases in size, the amount of genetic material remains the same. As a result, the ability of the nucleus to control the cell decreases.

Various checkpoints during the cell cycle evaluate conditions to determine whether cell activities in preparation for cell division should continue. The G_1 checkpoint during the G_1 phase determines if preparations should continue or if the cell should enter the G_0 state with no subsequent cell division. The G_2 checkpoint during the G_2 phase checks for accurate DNA replication. The M checkpoint during metaphase ensures that the chromosomes are properly attached to the spindle fiber microtubules.

Cell division also depends on the presence of cyclin-dependent kinases, which activate, by phosphorylation, proteins that regulate the cell cycle. Cell division is influenced by the detection of external molecules, or growth factors, that are produced by other cells. Cell division is also promoted when neighboring cells are available for attachment (anchorage dependence) or prevented by the presence of too many neighboring cells (density-dependent inhibition).

c. If and when a cell divides is determined much like other metabolic activities, by enzymes. Enzymes are produced at specific points of the cell cycle that induce specific activities that prepare the cell for division. The production of these enzymes is affected by environmental factors (such as carcinogens or cell density), by internal conditions, and by genetic factors. In a transformed cell, a cell that has become cancerous, the normal cell-cycle checkpoints and other regulatory mechanisms fail. For example, most cancerous cells lack anchorage dependence, growing and dividing without the need to attach to nearby cells.

Be sure to write your answer in sections, as was done in this answer, responding separately to each part of the question and labeling each response with the appropriate letter. Also, since your time is very limited, you should not spend too much of it defining words, unless specifically requested to do so. The free-response section of the exam is not a vocabulary test. Rather, these questions are designed to evaluate your understanding of biological processes. Thus, you should focus on describing the process, using (but not defining) as much of the appropriate vocabulary as you can. By doing so, you demonstrate both an understanding of terminology and the biological process.

5. a. Meiosis consists of two groups of divisions: meiosis I and II. In prophase I, the nuclear membrane breaks down, the nucleolus disappears, and chromatin condenses into chromosomes. The MTOCs (which contain centrioles in animals) migrate to opposite poles, developing microtubules and the spindle apparatus between them. Synapsis occurs when homologous chromosomes pair. During synapsis, crossing over between nonsister chromatids of homologous pairs results in an exchange of genetic material. The microtubules connect to the kinetochores in the centromeres of the chromosomes and pull on the chromosomes to the metaphase plate. Metaphase I occurs when the chromosomes are aligned on the metaphase plate as homologous pairs. Anaphase I begins as each member of a homologous pair of chromosomes is pulled by the microtubules to opposite poles. Telophase I follows when nuclear membranes appear. Cytokinesis and a short interphase II may occur at this point. Prophase II begins in each daughter cell in the same manner as prophase I. However, synapsis does not occur, and at metaphase II, the chromosomes are spread over the metaphase plate without any kind of pairing. Anaphase II begins as each chromosome is separated into two chromatids (now called chromosomes) and pulled by the microtubules of the spindle apparatus to opposite poles. During telophase II, meiosis is concluded as cytokinesis separates the nuclei into four haploid cells, each containing half the number of chromosomes of the original parent cell.

b. Meiosis is a reduction division that occurs in sexual reproduction. It halves the number of chromosomes so that daughter cells are haploid. In humans, the daughter cells are the gametes (sperm and eggs) formed in the testes and ovaries. Gametes fuse to form a diploid zygote, which then grows into a multicellular organism by mitotic divisions. In other organisms, meiosis may produce haploid spores, which divide by mitosis to grow into multicellular haploid organisms.

c. There are three points during meiosis and sexual reproduction where genetic material is rearranged to create genetic variation. First, crossing over during metaphase I results in an exchange of genetic material between nonsister chromatids of homologous chromosomes. Chromosomes, previously of either paternal or maternal origin, now contain genetic material from both parents. Second, homologous chromosome pairs randomly align across the metaphase plate in metaphase I. As a result, chromosomes migrating to one pole are a random mixture of paternal and maternal chromosomes. Third, the zygote is a combination of a randomly selected egg and a sperm. As a result of these random arrangements of chromosomes, daughter cells are genetically variable.