Chapter 12

The Cell Cycle

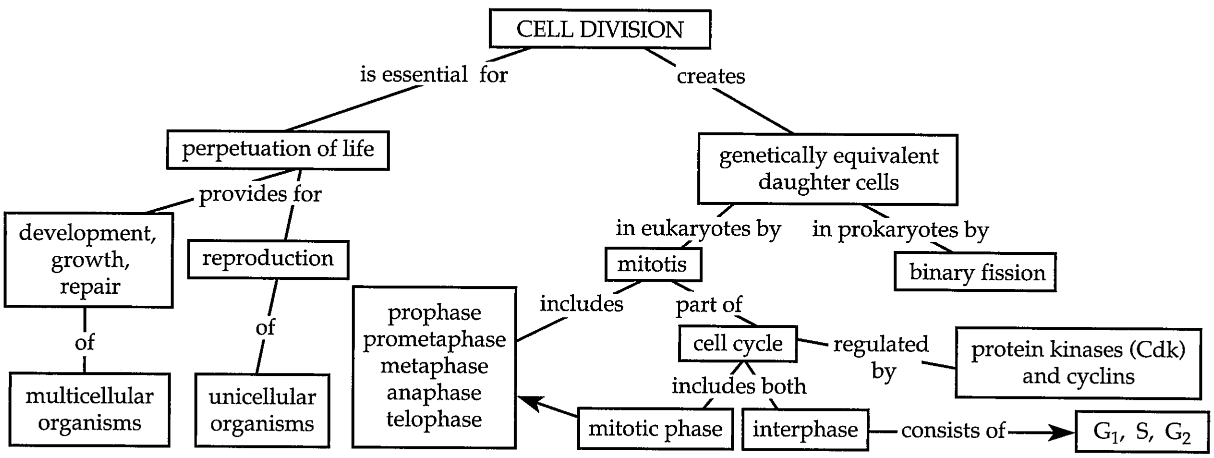
Key Concepts

12.1 Cell division results in genetically identical daughter cells

12.2 The mitotic phase alternates with interphase in the cell cycle

12.3 The cell cycle is regulated by a molecular control system

Framework



Chapter Review

Cell division creates duplicate offspring in unicellular organisms and provides for growth, development, and repair in multicellular organisms. The **cell cycle** extends from the creation of a new cell by the division of its parent cell to its own division into two cells.

12.1 Cell division results in genetically identical daughter cells

The process of re-creating a structure as intricate as a cell necessitates the exact duplication and equal division of the DNA containing the cell's genetic program.

Cellular Organization of the Genetic Material A cell's complete complement of DNA is called its **genome.** Each diploid eukaryotic species has a characteristic number of **chromosomes** in each **somatic cell;** reproductive cells, or **gametes** (egg and sperm), have half that number of chromosomes.

Each chromosome is a very long DNA molecule with associated proteins that help to structure the chromosome and control the activity of the genes. This DNA–protein complex is called **chromatin.**

Distribution of Chromosomes During Cell Division Prior to cell division, a cell copies its DNA and each chromosome densely coils and shortens. Replicated chromosomes consist of two identical **sister chromatids,** attached in their condensed form at a specialized region called a **centromere.** The two sister chromatids separate during **mitosis** (the division of the nucleus), and then the cytoplasm divides during **cytokinesis,** producing two separate, genetically equivalent daughter cells.

A type of cell division called **meiosis** produces daughter cells that have half the number of chromosomes of the parent cell. With the fertilization of egg and sperm, which were formed (in animals) by meiosis, the chromosome number is restored in the somatic cells of the new offspring.

■ INTERACTIVE QUESTION 12.1

a. How many chromosomes do you have in your somatic cells?

b. How many chromosomes in your gametes?

c. How many chromatids in one of your body cells that has duplicated its chromosomes prior to mitosis?

12.2 The mitotic phase alternates with interphase in the cell cycle

Phases of the Cell Cycle The cell cycle consists of the **mitotic (M) phase,** which includes mitosis and cytokinesis, and **interphase,** during which the cell grows and duplicates its chromosomes. Interphase, usually lasting 90% of the cell cycle, includes the **G_1 phase,** the **S phase,** and the **G_2 phase.** Mitosis is conventionally described in five subphases: **prophase, prometaphase, metaphase, anaphase,** and **telophase.**

■ INTERACTIVE QUESTION 12.2

a. How are the three subphases of interphase alike?

b. What key event happens during the S phase?

The Mitotic Spindle: A Closer Look The **mitotic spindle** consists of fibers made of microtubules and associated proteins. The assembly of the spindle begins in the **centrosome,** or microtubule-organizing center. A pair of centrioles is centered in each centrosome of an animal cell, but centrioles are not required for normal spindle operation. The single centrosome replicates during interphase. As spindle microtubules are formed, the two centrosomes move to opposite poles of the cell, and are called *spindle poles.* Radial arrays of microtubules, called **asters,** extend from the centrosomes in animal cells.

During prophase, the nucleoli disappear and the chromatin fibers coil and fold into visible chromosomes, consisting of sister chromatids joined at the centromere. During prometaphase, some of the spindle microtubules attach to each chromatid's **kinetochore,** a structure of protein associated with DNA located at the centromere region. Nonkinetochore microtubules (or "polar" microtubules) extend out from each centrosome and overlap at the midline. Alternate tugging on the chromosome by opposite kinetochore microtubules moves the chromosome to the midline of the cell. At metaphase, the chromosomes are aligned at the **metaphase plate,** across the midline of the spindle.

The proteins joining sister chromatids are inactivated in anaphase, and the now separate chromosomes move toward the poles. Motor proteins "walk" a chromosome along the kinetochore microtubules as these shorten by depolymerizing at their kinetochore end. The extension of the spindle poles away from each other as an animal cell elongates is probably due to the overlapping nonkinetochore microtubules walking past each other, also using motor proteins.

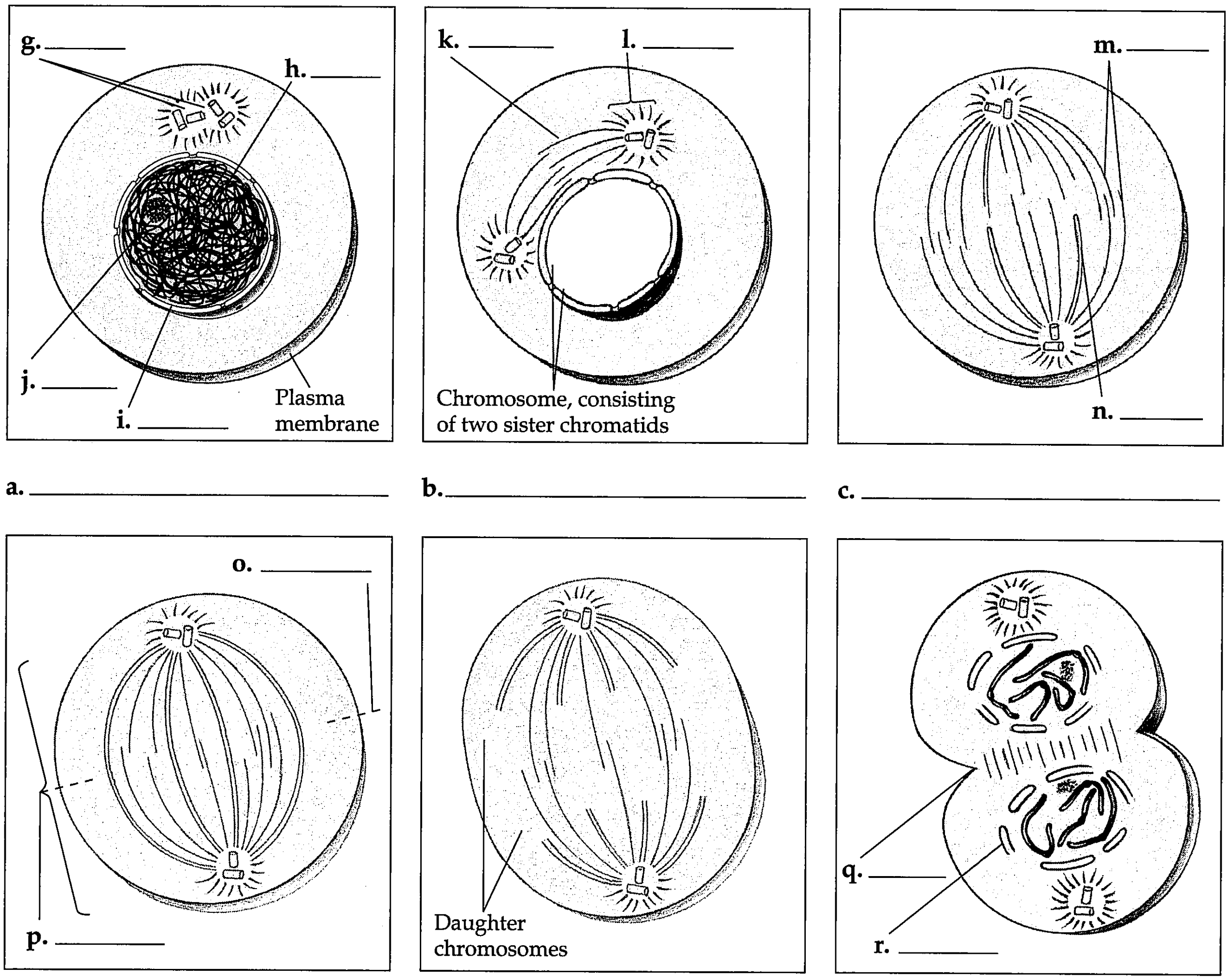
During telophase, equivalent sets of chromosomes gather at the two poles of the cell. Nuclear envelopes form, nucleoli reappear, and cytokinesis begins.

Cytokinesis: A Closer Look **Cleavage** is the process that separates the two daughter cells in animals. A **cleavage furrow** on the cell surface forms, as a ring of actin microfilaments interacting with myosin proteins begins to contract on the cytoplasmic side of the membrane. The cleavage furrow deepens until the dividing cell is pinched in two.

In plant cells, a **cell plate** forms from the fusion of membrane vesicles derived from the Golgi apparatus. The membrane of the enlarging cell plate joins with the plasma membrane, separating the two daughter cells. A new cell wall develops between the cells from the contents of the cell plate.

■ INTERACTIVE QUESTION 12.3

The following diagrams depict interphase and the five subphases of mitosis in an animal cell. Assuming that this cell has four chromosomes, sketch the chromosomes as they would appear in each subphase. Identify the stages and label the indicated structures.



a. ______________________ b. ______________________ c. ______________________

d. ______________________ e. ______________________ f. ______________________

Binary Fission Prokaryotes reproduce by a process known as **binary fission.** The *bacterial chromosome,* a single circular DNA molecule, begins to replicate at the **origin of replication** and these duplicated origins move apart by an unknown mechanism, ending up apparently anchored at opposite poles of the cell. Replication is completed as the cell doubles in size, and the plasma membrane grows inward to divide the two identical daughter cells.

The Evolution of Mitosis Evidence for the evolution of mitosis from bacterial cell division includes the relatedness of several proteins involved in both types of division and the possible intermediate stages seen in some unicellular algae, in which chromosomal division takes place within an intact nuclear envelope.

12.3 The cell cycle is regulated by a molecular control system

Normal growth, development, and maintenance depend on proper control of the timing and rate of cell division.

Evidence for Cytoplasmic Signals Experiments that fuse two cells at different phases of the cell cycle indicate that cytoplasmic chemical signals drive the cell cycle.

The Cell Cycle Control System A **cell cycle control system,** consisting of a set of molecules that function cyclically, coordinates the events of the cell cycle.

Important internal and external signals are monitored to determine whether the cell cycle will proceed past the three main **checkpoints** in the G_1, G_2, and M phases. If a mammalian cell does not receive a go-ahead signal at the G_1 checkpoint, called the "restriction point," the cell will usually exit the cell cycle to a nondividing state called the **G_0 phase.**

Protein kinases are enzymes that activate or inactivate other proteins by phosphorylating them. The changing concentrations of **cyclins**, regulatory proteins that attach to these kinases, affect the activity of **cyclin-dependent kinases,** or **Cdks.**

A cyclin–Cdk complex called **MPF,** for maturation or M-phase-promoting factor, triggers passage past the G_2 checkpoint into M phase. In addition to phosphorylating proteins and other kinases that initiate mitotic events, MPF activates a protein breakdown process that destroys its cyclin and thus MPF activity during anaphase. The Cdk portion of the complex remains to associate with new cyclin synthesized during S and G_2 phases of the next cycle.

Other Cdk proteins and cyclins appear to control the movement of a cell past the G_1 checkpoint.

■ INTERACTIVE QUESTION 12.4

a. What is MPF?

b. Describe the relative concentrations of MPF and its constituent molecules throughout the cell cycle:

MPF

Cdk

cyclin

An internal signal is required to move past the M-phase checkpoint into anaphase. Kinetochores that are not yet attached to spindle microtubules release a signal molecule that keeps active the proteins holding chromatids together until all chromosomes are attached to the spindle at the metaphase plate.

Growing cells in cell culture has allowed researchers to identify chemical and physical factors that affect cell division. Certain nutrients and regulatory proteins called **growth factors** have been found to be essential for cells to divide in culture. Mammalian fibroblast cells have receptors on their plasma membranes for *platelet-derived growth factor (PDGF),* which is released from blood platelets at the site of an injury. Binding of PDGF initiates a signal-transduction pathway that stimulates cell division.

Density-dependent inhibition of cell division is related to diminishing supplies of growth factors and essential nutrients. Most animal cells also show **anchorage dependence** and must be attached to a substratum in order to divide.

Loss of Cell Cycle Controls in Cancer Cells Cancer cells escape from the body's normal control mechanisms. When grown in cell culture, cancer cells do not exhibit density-dependent inhibition and may continue to divide indefinitely instead of stopping after the typical 20 to 50 divisions of normal mammalian cells.

When a normal cell is **transformed** or converted to a cancer cell, the body's immune system usually destroys it. If it proliferates, a mass of abnormal cells develops within a tissue. **Benign tumors** remain at their original site and can be removed by surgery. **Malignant tumors** cause cancer as they invade and disrupt the functions of one or more organs. Malignant tumor cells may have abnormal metabolism and unusual numbers of chromosomes. They lose their attachments to other cells and may **metastasize,** entering the blood and lymph systems and spreading to other sites. Radiation and chemicals are used to treat tumors that metastasize. Much remains to be learned about control of the cell division processes of both normal and cancerous cells.

Word Roots

ana- = up, throughout, again (*anaphase:* the mitotic stage in which the chromatids of each chromosome have separated and the daughter chromosomes are moving to the poles of the cell)

bi- = two (*binary fission:* a type of cell division in which a cell divides in half)

centro- = the center; **-mere** = a part (*centromere:* the narrow "waist" of a condensed chromosome)

chroma- = colored (*chromatin:* DNA and the various associated proteins that form eukaryotic chromosomes)

cyclo- = a circle (*cyclin:* a regulatory protein whose concentration fluctuates cyclically)

cyto- = cell; **-kinet** = move (*cytokinesis:* division of the cytoplasm)

gamet- = a wife or husband (*gamete:* a haploid egg or sperm cell)

gen- = produce (*genome:* a cell's endowment of DNA)

inter- = between (*interphase:* time when a cell metabolizes and performs its various functions)

mal- = bad or evil (*malignant tumor:* a cancerous tumor that is invasive enough to impair functions of one or more organs)

meio- = less (*meiosis:* a variation of cell division that yields daughter cells with half as many chromosomes as the parent cell)

meta- = between (*metaphase:* the mitotic stage in which the chromosomes are aligned in the middle of the cell, at the metaphase plate)

mito- = a thread (*mitosis:* the division of the nucleus)

pro- = before (*prophase:* the first mitotic stage in which the chromatin is condensing)

soma- = body (*centrosome:* a nonmembranous organelle that functions throughout the cell cycle to organize the cell's microtubules)

telos- = an end (*telophase:* the final stage of mitosis in which daughter nuclei are forming and cytokinesis has typically begun)

trans- = across; **-form** = shape (*transformation:* the process that converts a normal cell into a cancer cell)

Structure Your Knowledge

1. Describe the life of one chromosome as it proceeds through an entire cell cycle, starting with G_1 of interphase and ending with telophase of mitosis.
2. Draw a sketch of one half of a mitotic spindle. Identify and list the functions of the components.
3. In this photomicrograph of cells in an onion root tip, identify the cell cycle phases for the indicated cells.

a. __________

b. __________

c. __________

d. __________

Test Your Knowledge

FILL IN THE BLANK: *Identify the appropriate phase of the cell cycle.*

______ 1. most cells that will no longer divide are in this phase

______ 2. sister chromatids separate and chromosomes move apart

______ 3. mitotic spindle begins to form

______ 4. cell plate forms or cleavage furrow pinches cells apart

______ 5. chromosomes replicate

______ 6. chromosomes line up at equatorial plane

______ 7. nuclear membranes form around separated chromosomes

______ 8. chromosomes become visible

______ 9. kinetochore–microtubule interactions move chromosomes to midline

______ 10. restriction point occurs in this phase

MULTIPLE CHOICE: *Choose the one best answer.*

1. One of the major differences in the cell division of prokaryotic cells compared to eukaryotic cells is that
   a. cytokinesis does not occur in prokaryotic cells.
   b. genes are not replicated on chromosomes in prokaryotic cells.
   c. the duplicated chromosomes are attached to the nuclear membrane in prokaryotic cells and are separated from each other as the membrane grows.
   d. the chromosomes do not separate along a mitotic spindle in prokaryotic cells.
   e. the chromosome number is reduced by half in eukaryotic cells but not prokaryotic cells.

2. A plant cell has 12 chromosomes at the end of mitosis. How many *chromosomes* would it have in the G_2 phase of its next cell cycle?
   a. 6
   b. 9
   c. 12
   d. 24
   e. It depends on whether it is undergoing mitosis or meiosis.

3. How many *chromatids* would this plant cell have in the G_2 phase of its cell cycle?
   a. 6
   b. 9
   c. 12
   d. 24
   e. 48

4. The longest part of the cell cycle is
   a. prophase.
   b. G_1 phase.
   c. G_2 phase.
   d. mitosis.
   e. interphase.
5. In animal cells, cytokinesis involves
   a. the separation of sister chromatids.
   b. the contraction of the contractile ring of microfilaments.
   c. depolymerization of kinetochore microtubules.
   d. a protein kinase that phosphorylates other enzymes.
   e. sliding of nonkinetochore microtubules past each other.
6. Humans have 46 chromosomes. That number of chromosomes will be found in
   a. cells in anaphase.
   b. the egg and sperm cells.
   c. the somatic cells.
   d. all the cells of the body.
   e. only cells in G_1 of interphase.
7. Sister chromatids
   a. have one-half the amount of genetic material as does the original chromosome.
   b. start to move along kinetochore microtubules toward opposite poles during telophase.
   c. each have their own kinetochore.
   d. are formed during prophase.
   e. slide past each other along nonkinetochore microtubules.
8. Which of the following would *not* be exhibited by cancer cells?
   a. changing levels of MPF concentration
   b. passage through the restriction point
   c. density-dependent inhibition
   d. metastasis
   e. mitotic phase of the cell cycle
9. Which of the following is *not* true of a cell plate?
   a. It forms at the site of the metaphase plate.
   b. It results from the fusion of microtubules.
   c. It fuses with the plasma membrane.
   d. A cell wall is laid down between its membranes.
   e. It forms during telophase in plant cells.
10. A cell that passes the restriction point in G_1 will most likely
    a. undergo chromosome duplication.
    b. have just completed cytokinesis.
    c. continue to divide only if it is a cancer cell.
    d. show a drop in MPF concentration.
    e. move into the G_0 phase.
11. The rhythmic changes in cyclin concentration in a cell cycle are due to
    a. its increased production once the restriction point is passed.
    b. the cascade of increased production once its enzyme is phosphorylated by MPF.
    c. its degradation, which is initiated by active MPF.
    d. the correlation of its production with the production of Cdk.
    e. the binding of the growth factor PDGF.
12. In a plant cell, a centrosome functions in the formation of
    a. the cell plate.
    b. kinetochores.
    c. duplicate chromosomes.
    d. centromeres.
    e. microtubules of the spindle apparatus.
13. A cell in which of the following phases would have the *least* amount of DNA?
    a. G_0
    b. G_2
    c. prophase
    d. metaphase
    e. anaphase
14. What initiates the separation of sister chromatids in anaphase?
    a. the drop in MPF concentration
    b. a rapid rise in Cdk concentration
    c. movement past the G_2 checkpoint
    d. a signal pathway initiated by the binding of a growth factor
    e. the cessation of delay signals received from unattached kinetochores
15. Cells growing in cell culture that divide and pile up on top of each other are lacking
    a. anchorage dependence.
    b. density independence.
    c. PDGF.
    d. MPF.
    e. nutrients and growth factors.
16. Knowledge of the cell cycle control system will be most beneficial to the area of
    a. human reproduction.
    b. plant genetics.
    c. prokaryotic growth and development.
    d. cancer prevention and treatment.
    e. prevention and treatment of cardiovascular disease.