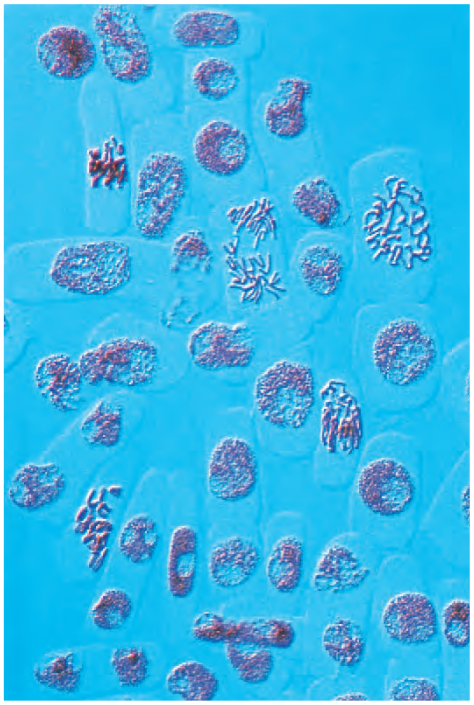
3

MITOSIS AND MEIOSIS

STUDY OBJECTIVES

1. To observe the morphology of chromosomes 48
2. To understand the processes of mitosis and meiosis 50
3. To analyze the relationships between meiosis and Mendel's rules 61

STUDY OUTLINE



Onion (*Allium cepa*) cells in various stages of mitosis.

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The zygote, or fertilized egg of higher organisms, is the starting point of most life cycles. This zygote then divides many times to produce an adult organism. In animals, the adults then produce gametes that combine to start the cycle again. In higher plants, the adult is a sporophyte that produces spores by genetic reduction. These spores develop into gametophytes, which may or may not be independent, and gametophytes produce gametes that fuse to form the zygote (fig. 3.1). (Numerous variations on these themes exist, some of which we will discuss later in this chapter or others.) The process of cell division includes a nuclear and a cytoplasmic component. Nuclear division **(karyokinesis)** has two forms, a nonreductional **mitosis** in which the mother and daughter cells have exactly the same genetic complement, and a reductional **meiosis** in which the products, gametes in animals and spores in higher plants, have approximately half the genetic material as the parent cell. Halving the amount ensures that, when the gametes recombine, the amount of genetic material in a zygote is the same from generation to generation. The division of the cytoplasm, resulting in two cells from one original cell, is termed **cytokinesis.** In this chapter, we examine the processes of mitosis and meiosis, which allow chromosomes, the gene vehicles, to properly apportion among daughter cells. We will discuss the engineering difficulties these processes pose and the relationship of meiosis to Mendel's rules.

Mendel's work was rediscovered at the turn of the century after being ignored for thirty-four years. One of the major reasons scientists could appreciate it in 1900 was that many of the processes that chromosomes undergo had been described. With those discoveries, a physical basis for genes had been found. That is, chromosomal behavior during gamete formation precisely fits Mendel's predictions for gene behavior during gamete formation. In this chapter, we look at the morphology of chromosomes and their behavior during somatic-cell division and gamete and spore formation.

Modern biologists classify organisms into two major categories: **eukaryotes,** organisms that have true, membrane-bound nuclei, and **prokaryotes,** organisms that lack true nuclei (table 3.1). Bacteria and blue-green algae are prokaryotes. All other organisms are eukaryotes. In most prokaryotes, the genetic material is a circle of double-stranded DNA (deoxyribonucleic acid) with some associated proteins; ancillary circles of double-stranded DNA called plasmids are also found frequently (see chapters 13 and 17). In eukaryotes, the genetic material, located in the nucleus (fig. 3.2), is linear, double-stranded DNA highly complexed with protein **(nucleoprotein).** In this chapter, we concentrate on the nuclear division processes of eukaryotes.

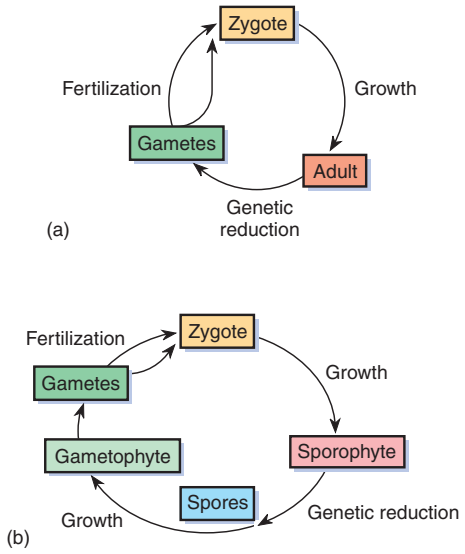


Figure 3.1 Generalized life cycle of (*a*) animals and (*b*) plants.

Table 3.1 Differences Between Prokaryotic and Eukaryotic Cells

	Prokaryotic Cells	Eukaryotic Cells
Taxonomic groups	Bacteria	All plants, fungi, animals, protists
Size*	Usually less than 5 μm in greatest dimension	Usually greater than 5 μm in smallest dimension
Nucleus	No true nucleus, no nuclear membrane	Nuclear membrane
Genetic material	One circular molecule of DNA, little protein	Linear DNA molecules complexed with histones
Mitosis and meiosis	Absent	Present

* See table 3.2 on page 48.

Table 3.2 Metric Units of Linear Measurement

Unit	Abbreviation	Size
meter	m	39.37 U.S. inches
centimeter	cm	10^{-2} meter
millimeter	mm	10^{-3} meter
micrometer	μm	10^{-6} meter
nanometer	nm	10^{-9} meter
Angstrom	Å	10^{-10} meter

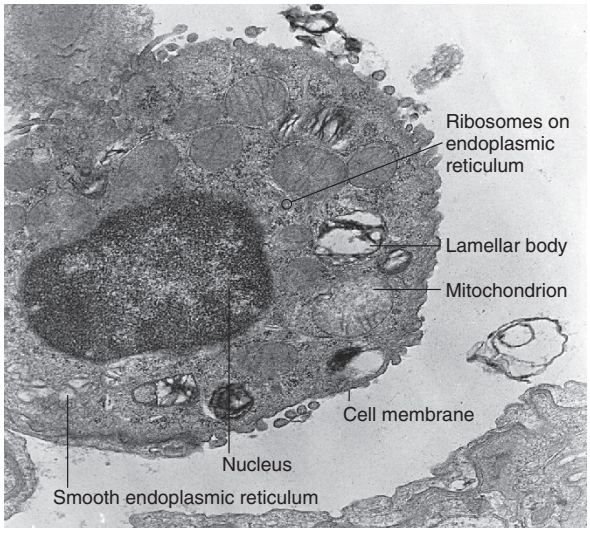


Figure 3.2 Mouse lung cell magnified 4,270x. (Courtesy of Wayne Rosenkrans.)

CHROMOSOMES

Chromosomes were discovered by C. von Nägeli in 1842. The term **chromosome,** which W. Waldeyer coined in 1888, means "colored body." Von Nägeli discovered chromosomes after staining techniques were developed that made them visible. The nucleoprotein material of the chromosomes is referred to as **chromatin.** When diffuse, chromatin is referred to as **euchromatin;** when condensed and readily visible, as **heterochromatin.**

Although all eukaryotes have chromosomes, in the **interphase** between divisions, they are spread out or diffused throughout the nucleus and are usually not identifiable. Each chromosome, with very few exceptions, has a distinct attachment point for fibers **(microtubules)** that make up the mitotic and meiotic spindle apparatuses. The attachment point occurs at a constriction in the chromosome termed the **centromere,** which is composed of several specific DNA sequences (see chapter 15). The **kinetochore** is the proteinaceous structure on the surface of the centromere to which microtubules of the spindle attach. Chromosomes can be classified according to whether the centromere is in the middle of the chromosome **(metacentric),** at the end of the chromosome **(telocentric),** very near the end of the chromosome **(acrocentric),** or somewhere in between (**subtelocentric** or **submetacentric;** figs. 3.3 and 3.4). For any particular chromosome, the position of the centromere is fixed. In various types of preparations, dark bands **(chromomeres)** are visible (see chapter 15).

Most higher eukaryotic cells are **diploid;** that is, all their chromosomes occur in pairs. One member of each pair came from each parent. **Haploid** cells, which include the reproductive cells (gametes), have only one copy of each chromosome. In the diploid state, members of the same chromosome pair are referred to as **homologous chromosomes** (homologues); the two make up a homologous pair.

The total chromosomal complement of a cell, the **karyotype,** can be photographed during mitosis and rearranged in pairs to make a picture called a karyotype or **idiogram** (fig. 3.5). From the idiogram it is possible to see whether the chromosomes have any abnormalities and to identify the sex of the organism. As you can see from figure 3.5, all of the homologous pairs are made up of identical partners, and are thus referred to as **homomorphic chromosome pairs.** A potential exception is the sex chromosomes, which in some species are of un-

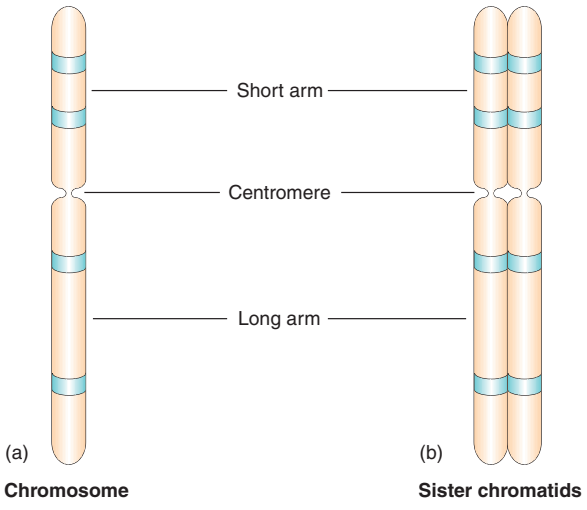


Figure 3.3 (*a*) Submetacentric chromosome and (*b*) submetacentric chromosome in mitosis. The chromosome is best seen after it has duplicated but before the identical halves (sister chromatids) separate.

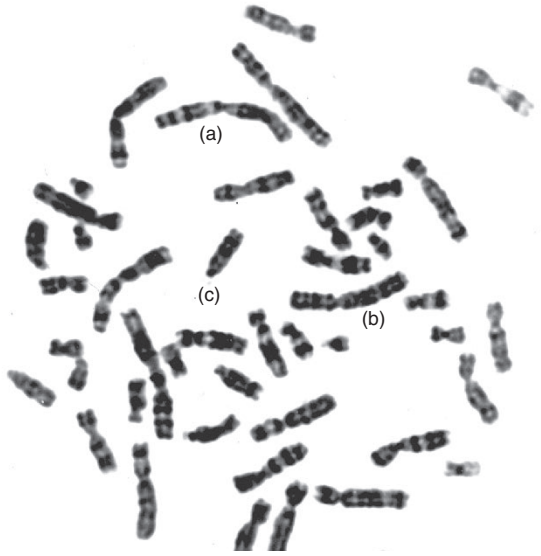


Figure 3.4 (*a*) Metacentric, (*b*) submetacentric, and (*c*) acrocentric chromosomes in human beings. Except in telocentric chromosomes, the centromere divides the chromosome into two arms. (Reproduced courtesy of Dr. Thomas G. Brewster, Foundation for Blood Research, Scarborough, Maine.)

equal size and are therefore called a **heteromorphic chromosome pair.**

The number of chromosomes individuals of a particular species possess is constant. Some species exist mostly in the haploid state or have long haploid intervals in their life cycle. For example, pink bread mold, *Neurospora crassa,* a fungus, has a chromosome number of seven ($n = 7$) in the haploid state. Its diploid number is, of course, fourteen ($2n = 14$). The diploid chromosome numbers of several species appear in table 3.3.

In eukaryotes, two processes partition the genetic material into offspring, or daughter, cells. One is the simple division of one cell into two. In this process, the two daughter cells must each receive an exact copy of the genetic material in the parent cell. The cellular process is simple cell division, and the nuclear process accompanying it is mitosis. In the other partitioning process, the genetic material must precisely halve so that fertilization will restore the diploid complement. The cellular process is gamete formation in animals and spore formation in higher plants, and the nuclear process is meiosis. The term *mitosis* comes from the Greek word for "thread," referring to a chromosome. The term *meiosis* comes from the Greek meaning "to lessen."

Chromosomes separate in both processes of nuclear division. The division of the cytoplasm of the cell, *cytokinesis*,

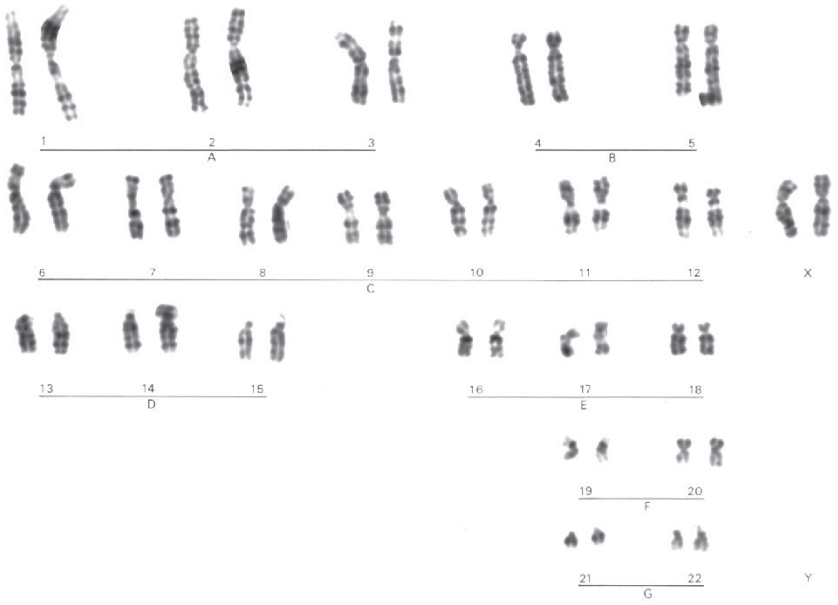


Figure 3.5 Idiogram or karyotype of a human female (two X chromosomes, no Y chromosome). A male would have one X and one Y chromosome. The chromosomes are grouped into categories (A–G, X, Y) by length and centromere position. Similar chromosomes are often distinguished by their chromomeres. (Reproduced courtesy of Dr. Thomas G. Brewster, Foundation for Blood Research, Scarborough, Maine.)

Table 3.3 Chromosome Number for Selected Species

Species	2*n*
Human being (*Homo sapiens*)	46
Garden pea (*Pisum sativum*)	14
Fruit fly (*Drosophila melanogaster*)	8
House mouse (*Mus musculus*)	40
Roundworm (*Ascaris* sp.)	2
Pigeon (*Columba livia*)	80
Boa constrictor (*Constrictor constrictor*)	36
Cricket (*Gryllus domesticus*)	22
Lily (*Lilium longiflorum*)	24
Indian fern (*Ophioglossum reticulatum*)	1,260

Note: 2*n* is the diploid complement. The fern has the highest known diploid chromosome number.

is less organized. In animals, a constriction of the cell membrane distributes the cytoplasm. In plants, the growth of a cell plate accomplishes the same purpose.

THE CELL CYCLE

The continuity of life depends on cells growing, replicating their genetic material, and then dividing, a process called the **cell cycle** (fig. 3.6). Although cells usually divide when they have doubled in volume, the control of this process is very complex and precise. Not only do all the steps have to occur in sequence, but the cell must also "know" when to proceed and when to wait. Continuing at inappropriate moments—for example, before the DNA has replicated or when the chromosomes or spindle are damaged—could have catastrophic consequences to a cell or a whole organism. Numerous stops occur during the cycle to assess whether the next step should proceed.

Early research into the cell cycle involved fusing cells in different stages of the cycle (such as the G_1, S, and G_2 phases; see fig. 3.6) to determine whether the cytoplasmic components of one cell would affect the behavior of the other. Results of these experiments led to the discovery of a protein complex called the **maturation-promoting factor (MPF)** because of its role in causing oocytes to mature. It is now also referred to as the **mitosis-promoting factor** since it initiates the mitosis phase of the cell cycle. Further research has shown that MPF is made of two proteins, one that oscillates in quantity during the cell cycle and one whose quantity is constant. The oscillating component is referred to as **cyclin;** the constant gene product is an enzyme controlled by the *cdc2* gene (*cdc* stands for *c*ell *d*ivision *c*ycle) called Cdc2p. Cdc2p is a kinase, an enzyme that phosphorylates other proteins, transferring a phosphate group from ATP to an amino acid of the protein it is acting on. (Phosphorylation controls many of the processes in mitosis and in metabolism in general; for example, the nuclear membrane begins to break down when its subunits are phosphorylated.) Because the Cdc2p kinase works when combined with cyclin, it is referred to as a **cyclin-dependent kinase (CDK).** Several of these kinase-cyclin combinations control stages of the cell cycle; the cyclin of the mitosis-promoting factor is called cyclin B. In general, cylin-dependent kinases are regulated by phosphorylation and dephosphorylation, cyclin levels, and activation or deactivation of inhibitors.

Normally, Cdc2p remains at high levels in the cell but does not initiate mitosis for two reasons. First, phosphate groups block its active site, the place on the enzyme that actually does the phosphorylating. Second, the enzyme can only function when it combines with a molecule of cyclin B, the protein that oscillates during the cell cycle. Cyclin B is at very low levels when mitosis ends. During ensuing cell growth, numbers of cyclin B molecules increase, combining with Cdc2p proteins until a critical quantity is reached. However, Cdc2p-cyclin B complexes are still not active. That requires the product of another gene to dephosphorylate the Cdc2p-cyclin B complex. At that point, the Cdc2p-cyclin B complex goes into action, initiating the changes that begin mitosis (fig. 3.7). Presumably the cell is ready for mitosis at that point, having

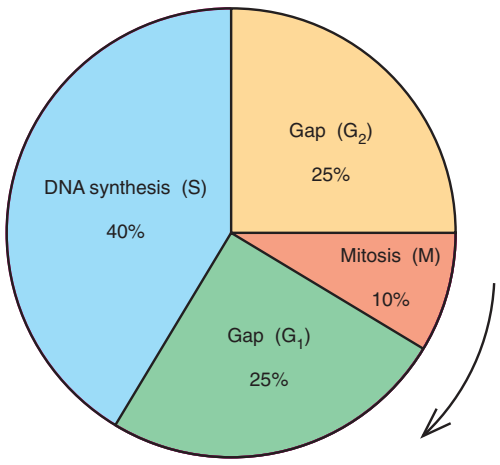


Figure 3.6 Cell cycle in the broad bean, *Vicia faba*. Total time in the cycle is under twenty hours. The DNA content of the cell doubles during the S phase and is then reduced back to its original value by mitosis.

gone through G1, S, and G2 phases (which we will discuss in detail later in the chapter).

Once mitosis has been initiated, cyclin B, along with other proteins that have served their purpose by this point in the cell cycle, breaks down with the help of a protein complex called the **anaphase-promoting complex (APC),** also called the **cyclosome.** The cyclosome works by attaching a **ubiquitin** molecule to the proteins that are to be broken down. (Ubiquitin is a polypeptide of 76 amino acids; it directs the attached protein into a breakdown pathway discussed in chapter 16.) Cdc2p is then phosphorylated to block its active site. The cell now completes mitosis and enters G_1; quantities of cyclin B are very low, and virtually no functioning Cdc2p-cyclin B remains (fig. 3.7). Thus, active Cdc2p is the kinase that controls the initiation of mitosis.

Some points in the cell cycle, such as the initiation of mitosis, can be delayed until all necessary conditions are in place. These **checkpoints** allow the cell to make sure that various events have been "checked off" as completed before the next phase begins. **Surveillance mechanisms** that involve dozens of proteins, many just discovered, oversee these checkpoints. In the cell cycle, three checkpoints involve cyclin-dependent kinases; each has its own specific cyclin that initiates either the G_1, S, or mitosis phase. In addition, other checkpoints that don't involve cyclin-dependent kinases occur at other transition phases in the cell cycle.

Cell cycle control is of particular interest because the cell cycle routinely halts if there is genetic damage, giving the cell a chance to repair the damage before committing to cell division. If the damage is too extreme, the cell can enter a programmed cell death sequence, discussed in chapter 16. If these mechanisms fail, cancer may result. The genetic control of the cell cycle is one of the most active areas of current research.

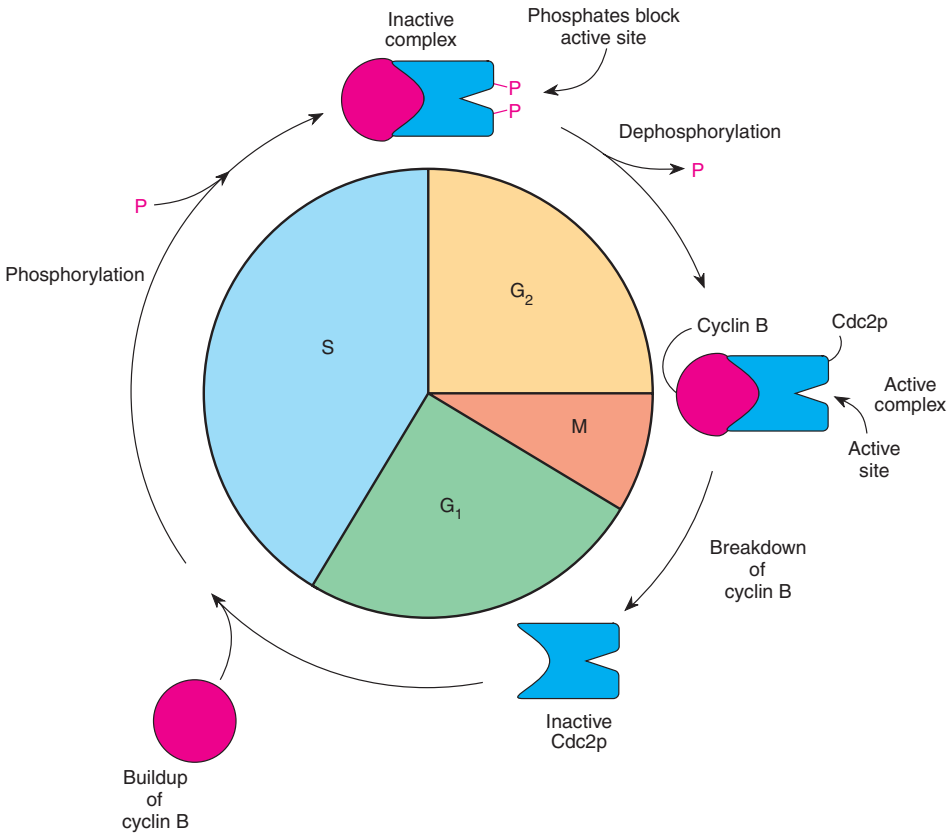


Figure 3.7 The proteins Cdc2p (CDK1) and cyclin B combine to form the maturation-promoting (or mitosis-promoting) factor. During mitosis, cyclin B is broken down. During G_1 and S phases, cyclin B builds up and combines with Cdc2P, which is then phosphorylated at the active site to render it inactive. Dephosphorylation, a process that begins to take place only after DNA replication is finished, produces an active maturation-promoting factor.

MITOSIS

Consider the engineering problem that mitosis must solve. Identical **chromatids,** called **sister chromatids,** the result of chromosomal replication, must separate so that each goes into a different daughter cell (see fig. 3.3). These chromatids are the visible manifestation of the chromosomal replication that has taken place in the S phase of the cell cycle. The chromatids are initially held together; each will be called a chromosome when it separates and becomes independent. Each of the two daughter cells then ends up with a chromosome complement identical to that of the parent cell. Mitosis is nature's elegant process to achieve that end—surely an engineering marvel.

Mitosis is a continuous process. However, for descriptive purposes, we can break it into four stages: **prophase, metaphase, anaphase,** and **telophase** (Greek: *pro-,* before; *meta-,* mid; *ana-,* back; *telo-,* end). Replication (duplication) of the genetic material occurs during the S phase of the cell cycle (see fig. 3.6). The timing of the four stages varies from species to species, from organ to organ within a species, and even from cell to cell within a given cell type.

The Mitotic Spindle

The process of mitosis involves an apparatus called the **spindle.** This structure is composed of microtubules, hollow cylinders made of protein subunits; each subunit is composed of one molecule of α tubulin and one of β tubulin; and each tubulin is the product of a different gene. (The spindle is named for the rounded rods, tapered at each end, once commonly used to hold yarn or thread.) Microtubules provide shape and structure to a eukaryotic cell as well as allow the cell to move its internal components and to move the cell itself with cilia and flagella. Motion occurs as the microtubules slide past each other, a vesicle of some kind slides along the microtubules, and the microtubules shorten. Two proteins make up the microtubule motors that allow motion: **kinesin** and **dynein.** Scientists have studied microtubules through protein chemistry, through mutant organisms, and through innovative methods such as by coupling tubulin subunits with fluorescing dyes to observe the microtubules in action.

Microtubules are in a dynamic equilibrium, with subunits constantly being added or removed at both ends. On any microtubule, more activity occurs at one end than the other. The more active end of the tubule is called the plus end, the less active end the minus end (fig. 3.8). Both ends may be adding or removing subunits, or the plus end may be adding while the minus end is removing subunits. Generally, dynein causes movement toward the minus end, whereas kinesin causes movement toward the plus end of a microtubule, although exceptions exist.

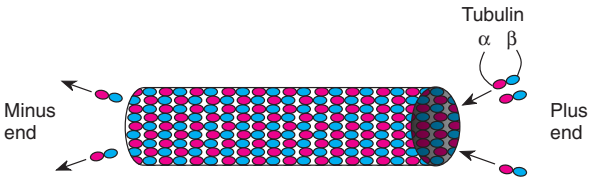


Figure 3.8 Microtubules are hollow tubes made of α and β tubulin subunits that are constantly being added or removed.

Microtubules are formed from active centers called **microtubule organizing centers. Centrioles,** composed of two cylinders—themselves composed of microtubules—are microtubule organizing centers for cilia and flagella. Under those circumstances, the centrioles are referred to as **basal bodies.** The centrioles were also originally believed to organize spindles. However, for most organisms, the microtubule organizing center is called the **centrosome.** In some organisms, such as fungi, a different cell organelle, the **spindle pole body,** serves this function. In most animals, the centrosome contains a centriole (fig. 3.9). However, the centriole is absent in most higher plants. Moreover, innovative ex-

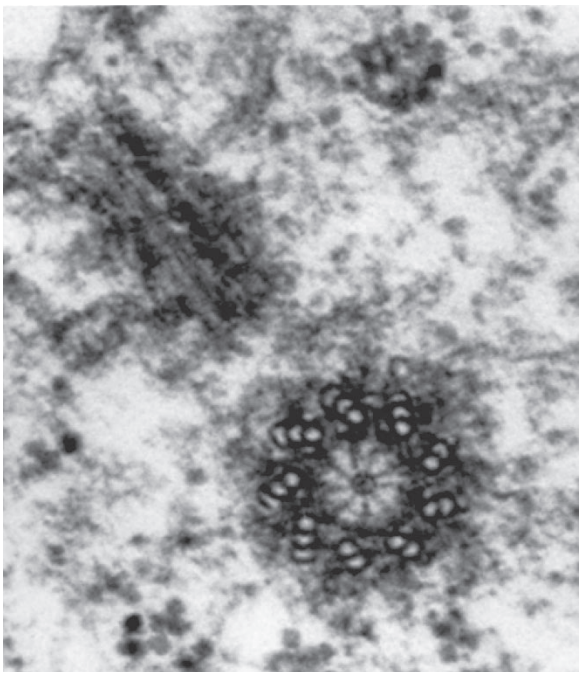


Figure 3.9 A centriole is composed of two barrels at right angles to each other. Each barrel is composed of nine tripartite units and a central cartwheel. Each of the three parts of a tripartite unit is a microtubule. Magnification 111,800×.
(Reproduced from *The Journal of Cell Biology,* 1968, Vol. 37, p. 381, by copyright permission of The Rockefeller University Press.)

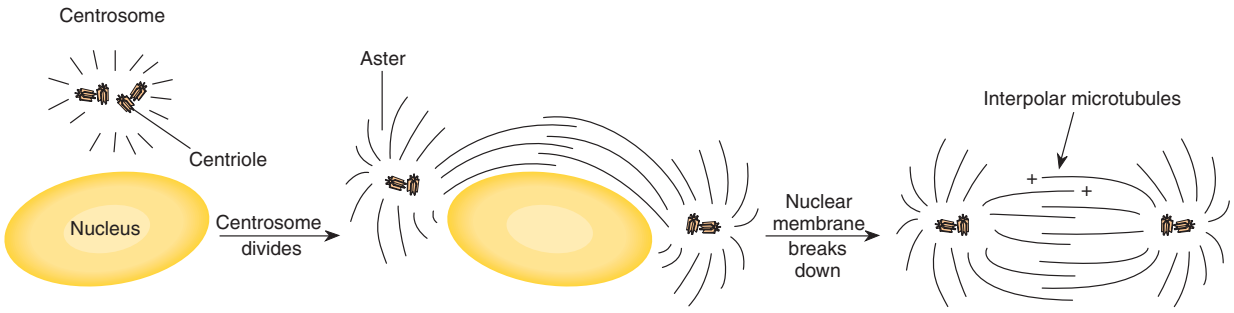


Figure 3.10 Early in mitosis, the centrosome divides, and the separating halves move to opposite poles of the cell. This creates a spindle in the middle of the cell after the nuclear membrane breaks down.

periments that removed the centrioles from cells that normally had them demonstrated that the centriole is not necessary for spindle formation. So, although we used to believe that the centriole formed the spindle in many organisms, we now know that the spindle is usually organized around the centrosome, which can function in this capacity without a centriole.

The centriole, when present, replicates during the S and G_2 phases. When mitosis begins, the centrosome divides and moves to opposite poles of the cell, around the nucleus (fig. 3.10). The centrosomes trail microtubules, forming the spindle, that at this point begin at each centrosome and overlap in the middle of the cell. These are called **interpolar microtubules.** Microtubules also spread out from the centrosome in the opposite direction from the spindle itself, forming an **aster** (see fig. 3.10). The minus ends of microtubules emanate from the centrosome and the plus ends overlap in the middle of the cell. A third form of tubulin, γ tubulin, is needed to begin the formation of a microtubule.

Prophase

This stage of mitosis is characterized by the formation of the spindle and a shortening and thickening of the chromosomes so that individual chromosomes become visible. (We will discuss details of the molecular structure of the eukaryotic chromosome and the processes of coiling and shortening in chapter 15.) At this time also, the nuclear envelope (membrane) disintegrates and the **nucleolus** disappears (fig. 3.11). The nucleolus is a darkly stained body in the nucleus that is involved in ribosome construction and that forms around a **nucleolar organizer** locus on one of the chromosome pairs. The number of nucleoli varies in different species, but in the simplest case there are two nucleolar organizers per nucleus, one each on the two members of a homologous pair of chromosomes. Nucleoli re-form after mitosis.

As prophase progresses, each chromosome is composed of two identical (sister) chromatids (see fig. 3.3); the chromosomes continue to shorten and thicken. The centromeres have already divided, and no new DNA synthesis is needed for the process to be completed. At this point, the sister chromatids are kept together by a complex, called **cohesin,** made up of at least four different protiens.

Spindle fibers are initially nucleated at the centrosome and grow outward into the cytoplasm (fig. 3.12). Some of these fibers "capture" a kinetochore, the proteinaceous complex at the centromere of each sister chromatid; these fibers are called **kinetochore microtubules.** At first, one kinetochore or the other randomly attaches to a spindle fiber. As the microtubules further move the chromosomes and as new microtubules attach and old microtubules break, each sister kinetochore eventually attaches to microtubules emanating from different poles. This ensures that sister chromatids move to opposite poles during anaphase. The number of microtubules that attach to each kinetochore differs in different species. It seems that 1 attaches to each kinetochore in yeast, 4 to 7 attach to each kinetochore in the cells of a rat fetus, and 70 to 150 attach in the plant *Haemanthus* (see fig. 3.12).

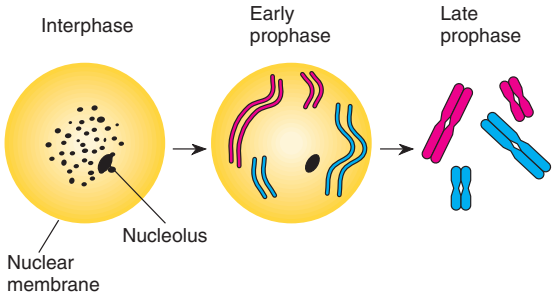


Figure 3.11 Nuclear events during interphase and prophase of mitosis. In this cell, $2n = 4$, consisting of one pair of long and one pair of short metacentric chromosomes. Maternal chromosomes are *red;* paternal chromosomes are *blue.* Note that each chromosome consists of two chromatids when the cell enters mitosis.

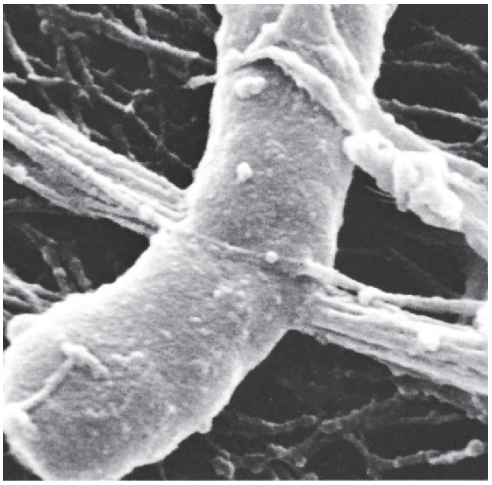


Figure 3.12 Scanning electron micrograph of the centromeric region of a metaphase chromosome from the plant *Haemanthus katherinae*. Spindle fiber bundles on either side of the centromere extend in opposite directions. A fiber not connected to the kinetochore is visible lying over the centromere. These fibers are 60 to 70 nm in diameter. (Waheeb K. Heneen, "The centromeric region in the scanning electron microscope," *Hereditas,* 97 (1982): 311–14. Reproduced by permission.)

Metaphase

During metaphase, the chromosomes move to the equator of the cell. With the attachment of the spindle fibers and the completion of the spindle itself, the chromosomes jockey into position in the equatorial plane of the spindle, called the **metaphase plate.** This happens as kinetochore microtubules exert opposing tension on the two sister kinetochores. Alignment of the chromosomes on this plate marks the end of metaphase (fig. 3.13).

Anaphase

During anaphase, the sister chromatids separate and move toward opposite poles on the spindle. The physical separation of the sister chromatids and their movement to opposite poles are two separate activities. Chromatid separation represents a checkpoint in the process of mitosis; a surveillance mechanism will not allow the process to continue until all chromosomes are lined up on the metaphase plate with their sister kinetochores held by microtubules from opposite poles. The surveillance mechanism somehow checks the physical tension the spindle fibers exert on a pair of sister chromatids; an unpaired chromatid can delay or stop the process. Initially, an inhibitory protein called **securin** binds an enzyme called **separin** that can break down cohesin, the complex holding the chromatids together. At the correct moment, the cyclosome ubiquitinates the inhibitor, causing it to break down and freeing the separin to break down cohesin. This liberates the sister chromatids from each other (and is the instant when chromatids become chromosomes).

The spindle then separates the sister chromatids in two stages, called **anaphase A** and **anaphase B.** In anaphase A, the chromosomes move toward the poles (fig. 3.14). During this process, the kinetochore itself acts as a microtubule motor, disassembling microtubules as it moves down them, pulling the chromosomes along (fig. 3.15). Thus, metacentric chromosomes appear V-shaped (as in fig. 3.15), subtelocentrics appear J-shaped, and telocentrics appear rod-shaped. In anaphase B, the spindle itself elongates as overlapping interpolar microtubules slide apart. The general elongation of the spindle pulls the chromosomes apart.

Telophase

At the end of anaphase (fig. 3.16), the separated sister chromatids (now full-fledged chromosomes) have been pulled to opposite poles of the cell. The cell now reverses the steps of prophase to return to the interphase state (fig. 3.17). The chromosomes uncoil and begin to direct protein synthesis. A nuclear envelope re-forms around each set of chromosomes, nucleoli re-form, and cytokinesis takes place. The spindle breaks down into tubulin subunits; a residual of microtubules remains at

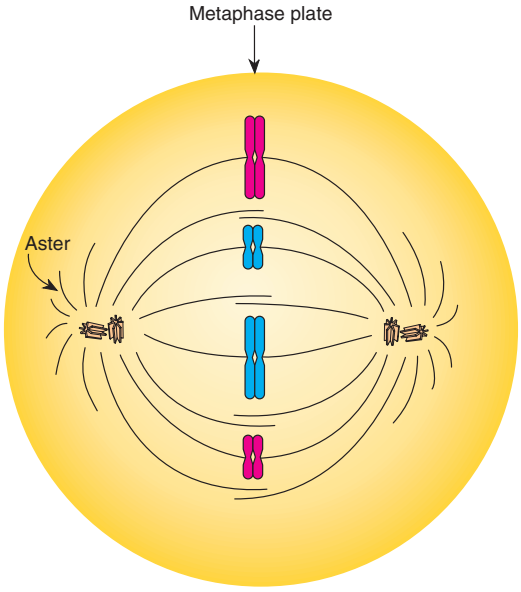
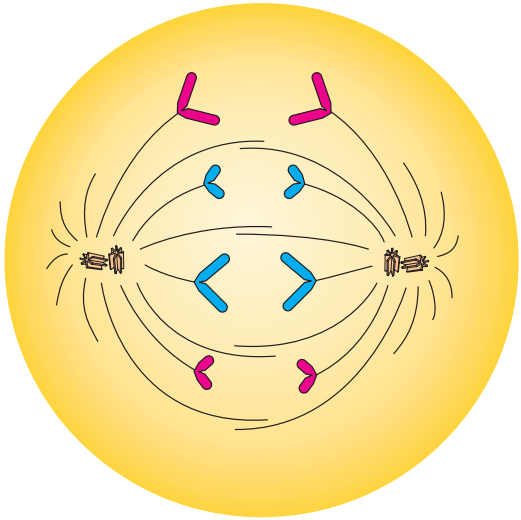


Figure 3.13 Metaphase of mitosis. In this cell, $2n = 4$. Maternal chromosomes are *red;* paternal chromosomes are *blue*.

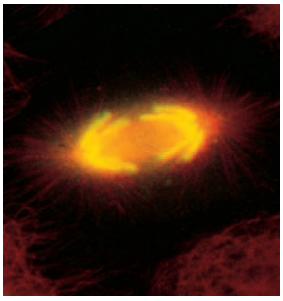
the center of the cell and seems to be involved in the formation of a constricting ring in animal cells or in the growth of a cell plate in plant cells. The cell has now entered the G_1 phase of the cell cycle (see fig. 3.6). Figure 3.18 summarizes mitosis.

The Significance of Mitosis

Cytokinesis and mitosis result in two daughter cells, each with genetic material identical to that of the parent cell. This exact distribution of the genetic material, in the form of chromosomes, to the daughter cells, ensures the stability of cells and the inheritance of traits from one cell generation to the next. Cells have evolved complex life functions; with mitosis, they will produce offspring cells with these same capabilities. With this stability assured, single-celled organisms could thrive and multicellular organisms could evolve.



(a)



(b)

Figure 3.14 (*a*) The mitotic spindle during anaphase. In this cell, $2n = 4$. Maternal chromosomes are *red;* paternal chromosomes are *blue*. (*b*) Fluorescent microscope image of a cultured cell in anaphase. Microtubules are *red;* chromosomes (DNA) are stained *yellow*. ([*b*] John M. Murray, Department of Anatomy, University of Pennsylvania. Cover of *BioTechniques,* volume 7, number 3, March 1989. Reproduced with permission.)

MEIOSIS

Gamete formation presents an entirely new engineering problem to be solved. To form gametes in animals (and, for the most part, to form spores in plants), a diploid organism with two copies of each chromosome must form daughter cells that have only one copy of each chromosome. In other words, the genetic material must be reduced by half so that when gametes recombine to form zygotes, the original number of chromosomes is restored, not doubled.

If we were to try to engineer this task, we would first need to be able to recognize homologous chromosomes. We could then push one member of each pair into one daughter cell and the other into the other daughter cell. If we were unable to recognize homologues, we would not be able to ensure that each daughter cell received one and only one member of each pair. The cell solves this problem by pairing up homologous chromosomes during an extended prophase. The spindle apparatus then separates members of the homologous chromosome pairs, just as it separates sister chromatids during mitosis. But there is one complication. As in mitosis, cells entering meiosis have already replicated their chromosomes. Therefore, two nuclear divisions without an intervening chromosome replication are necessary to produce haploid gametes or

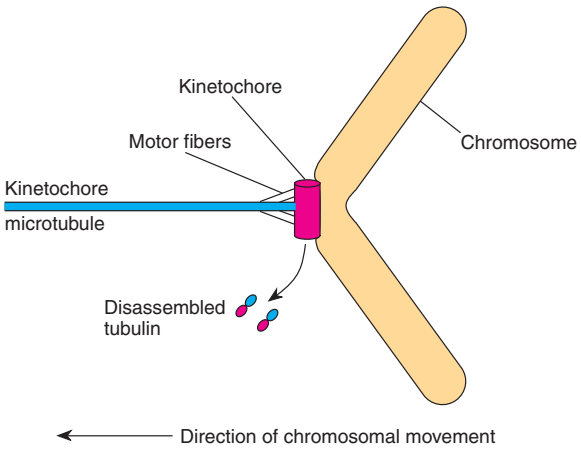


Figure 3.15 The kinetochore acts as a microtubule motor, pulling the chromosome along the kinetochore microtubules toward the pole. One microtubule is shown, although many may be present.

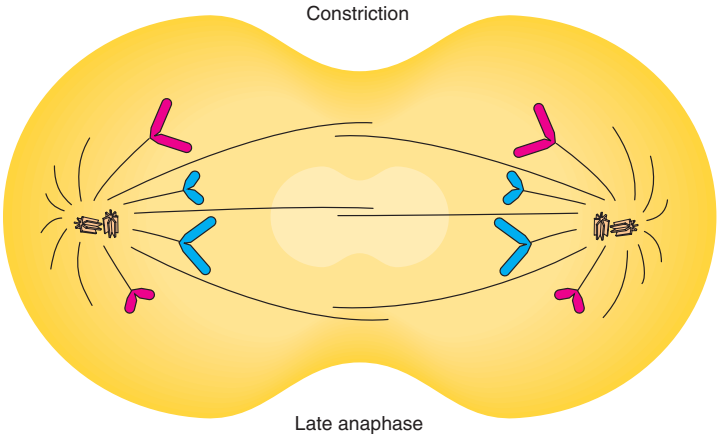


Figure 3.16 Late anaphase of mitosis; $2n = 4$. A constriction begins to form in the middle of the cell (in animals). Maternal chromosomes are *red;* paternal chromosomes are *blue*.

spores. Meiosis is, then, a two-division process that produces four cells from each original parent cell. The two divisions are known as meiosis I and meiosis II.

Unlike mitosis, meiosis occurs only in certain kinds of cells. In animals, meiosis begins in the primary gametocytes; in higher plants, the process takes place only in the spore-mother cells of the sporophyte generation (see fig. 3.1). At the end of this chapter, we review the processes of gamete and spore formation in animals and plants, respectively.

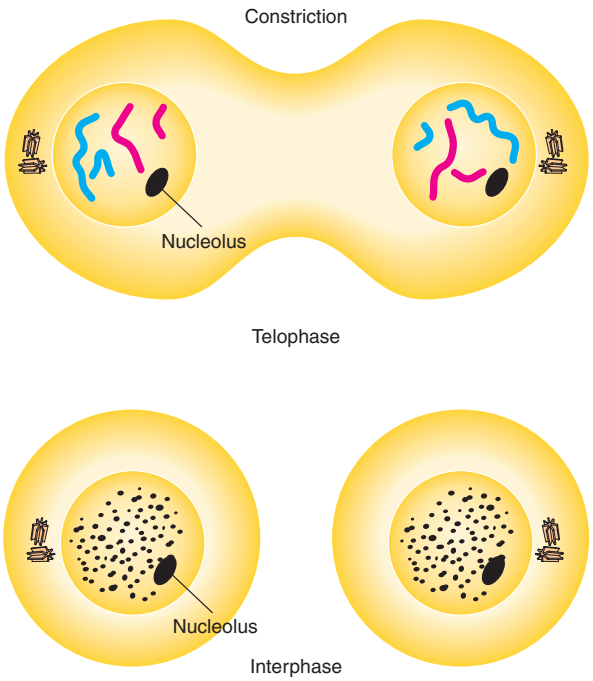


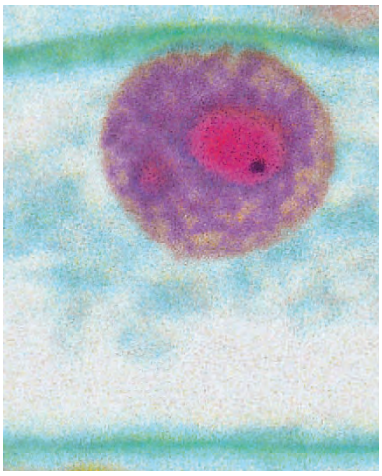
Figure 3.17 Telophase and interphase of mitosis; $2n = 4$. Maternal chromosomes are *red;* paternal chromosomes are *blue*.

Prophase I

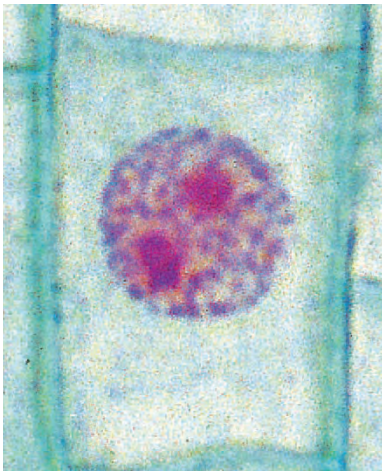
Cytogeneticists have divided the prophase of meiosis I into five stages: **leptonema, zygonema, pachynema, diplonema,** and **diakinesis** (Greek: *lepto-,* thin; *zygo-,* yoke-shaped; *pachy-,* thick; *diplo-,* double; *dia-,* across). A cell entering prophase I (leptotene stage) behaves similarly to one entering prophase of mitosis, with the centrosome duplicated and the spindle forming around the intact nucleus. (Note the adjectival forms—*leptotene*—versus the noun forms—*leptonema*—of the stage names.) As the chromosomes coil down in size during leptonema, they are visible as individual threads: sister chromatids are in such close apposition that they are not distinct. The chromosomes are more spread out than they are in mitosis, with dark spheres or bands called chromomeres interspersed.

The tips of the chromosomes are attached to the nuclear membrane in the leptotene stage (fig. 3.19). In the leptotene to zygotene transition, the tips of the chromosomes move until most end up in a limited region near each other. This forms an arrangement called a **bouquet stage.** Presumably, this arrangement helps homologous chromosomes find each other and begin the pairing process without becoming entangled.

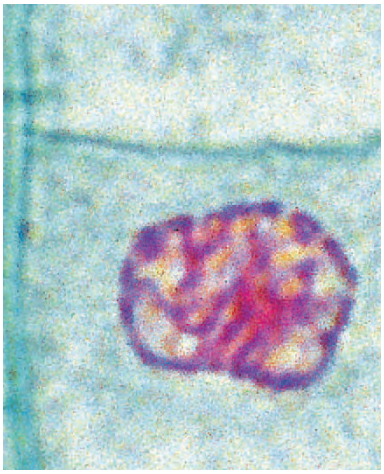
The pairing of homologous chromosomes marks the zygotene stage. Initial contact between identical regions of homologous chromosomes leads to a point-for-point pairing along their lengths. This process is referred to as **synapsis.** A proteinaceous complex, referred to as a



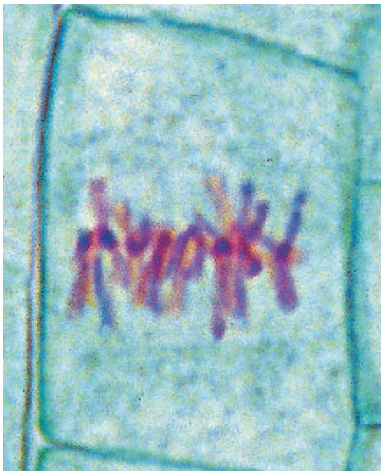
(a) Interphase



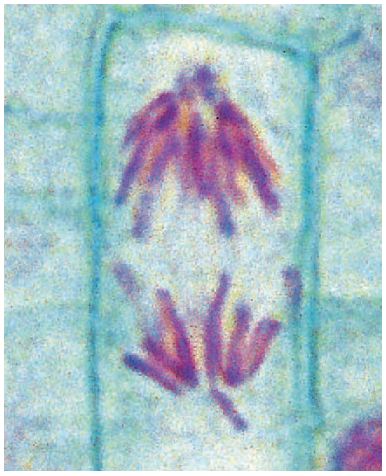
(b) Early prophase



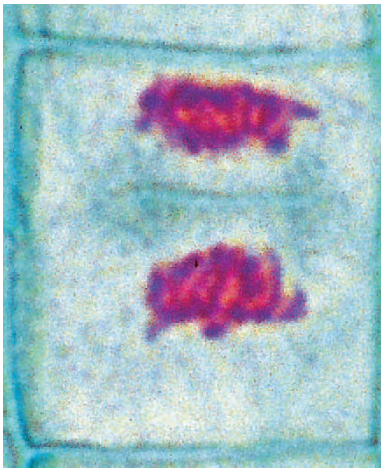
(c) Late prophase



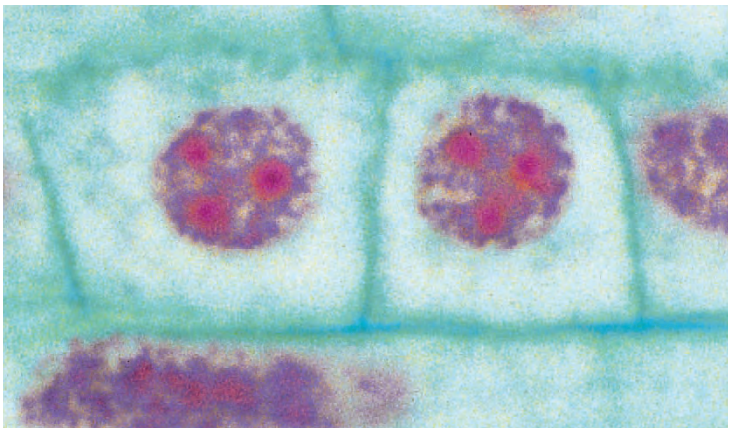
(d) Metaphase



(e) Anaphase



(f) Telophase



(g) Daughter cells

Figure 3.18 Cells in interphase and in various stages of mitosis in the onion root tip. The average cell is about 50 μm long. (© The McGraw-Hill Companies, Inc./Kingsley Stern, photographer.)

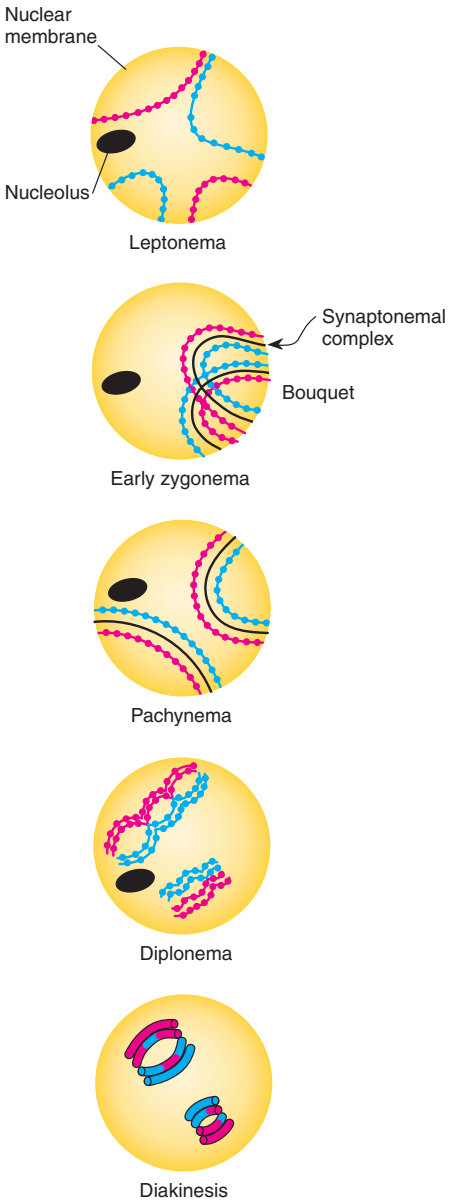


Figure 3.19 Prophase I of meiosis; $2n = 4$ (nuclei shown). Maternal chromosomes are *red;* paternal chromosomes are *blue*. Note that crossing over is evident at diplonema.

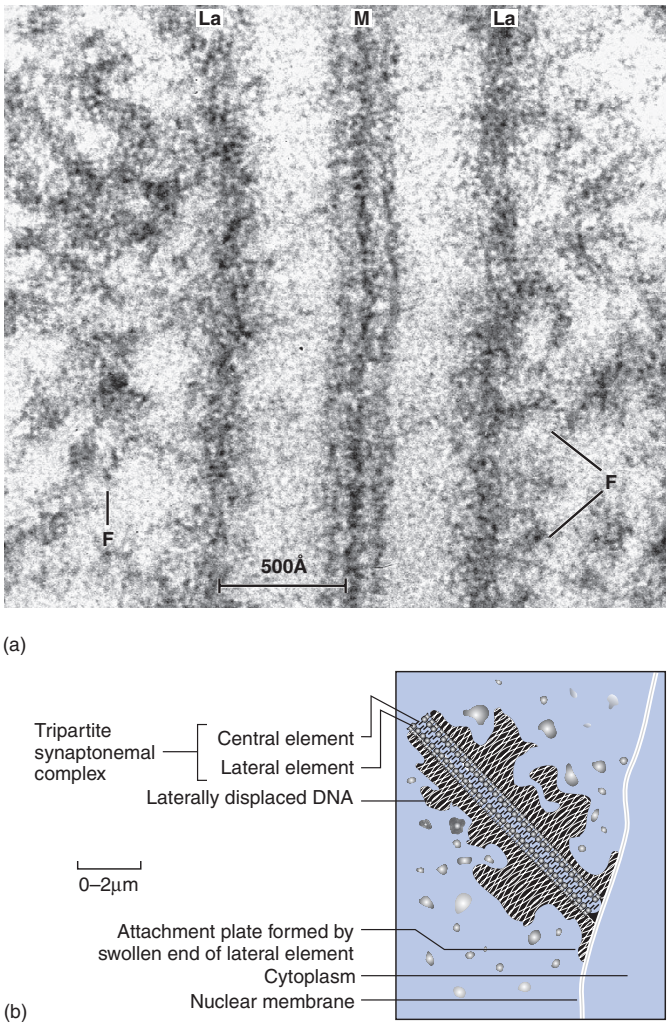


Figure 3.20 The synaptonemal complex. *(a)* In the electron micrograph, *M* is the central element, *La* are lateral elements, and *F* are chromosome fibers. Magnification 400,000×. *(b)* Diagram of the structure. ([*a*] R. Wettstein and J. R. Sotelo, "The molecular architecture of synaptonemal complexes," in E. J. DuPraw, ed., *Advances in Cell and Molecular Biology,* vol. 1 (New York: Academic Press, 1971), p. 118. Reproduced by permission. [*b*] From B. John and K. R. Lewis, *Chromosome Hierarchy.* Copyright © 1975 Oxford University Press, London, England. Reprinted by permission of the Oxford University Press.)

synaptonemal complex (fig. 3.20), appears between the homologous chromosomes and mediates synapsis in an unknown way. At this point, the chromosome figures are referred to as **bivalents,** one bivalent per homologous pair. The synapsis of all chromosomes marks the end of zygonema.

The chromosomes now continue to shorten and thicken, giving pachynema its name. During the entire prophase, **crossing over** takes place. When two chromatids come to lie in close proximity, enzymes can break both chromatid strands and reattach them differently (fig. 3.21). Thus, although genes have a fixed position on a chromosome, alleles that started out attached to a paternal centromere can end up attached to a maternal cen-

Figure 3.21 Crossing over in a tetrad during prophase of meiosis I. Maternal chromosomes are *red;* paternal chromosomes are *blue.* Note the exchange of chromosome pieces after the process is completed.

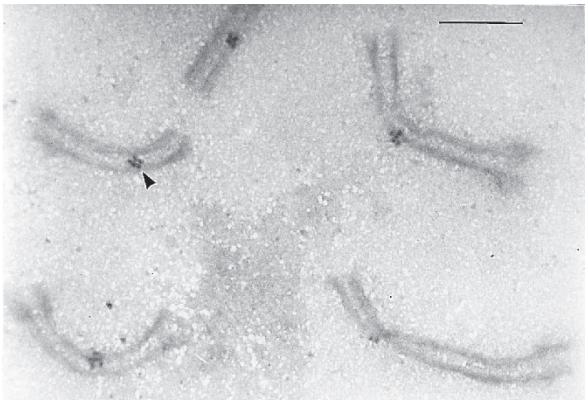
tromere. Crossing over can greatly increase the genetic variability in gametes by associating alleles that were not previously joined. (We examine the molecular mechanism of this process in chapter 12.) Before crossing over takes place, densely staining nodules are visible, first in zygonema and lasting through pachynema. These are called **recombination nodules** (fig. 3.22*a*); they are correlated with crossing over and presumably represent the enzymatic machinery present on the chromosomes.

As the chromosomes shorten and thicken further in diplonema, each chromosome can be seen to be made of two sister chromatids. Now the chromosome figures are referred to as **tetrads** because each is made up of four chromatids (see fig. 3.19). At about this time, the synaptonemal complex disintegrates in all but the areas of the **chiasmata** (singular: chiasma), the X-shaped configurations marking the places of crossing over (fig. 3.22*b*). Virtually all tetrads exhibit chiasmata; in cases in which no crossing over occurs, the tetrads tend to fall apart and segregate randomly. Thus, crossing over not only increases genetic diversity but also ensures the proper separation of homologous chromosomes. A meiosis-specific form of cohesin keeps sister chromatids together.

During the diplotene stage, chromosomes can again uncondense and become active. This is especially obvious in amphibians and birds, which produce a great amount of cytoplasmic nutrient for the future zygote. Recondensation of the chromosomes takes place at the end of diplonema. This stage can be very long; in human females, it begins in the fetus and does not complete until the egg is shed during ovulation, sometimes more than fifty years later. As prophase I moves into diakinesis, the chromosomes become very condensed (see fig. 3.19).

Metaphase I and Anaphase I

Metaphase I is marked by the breakdown of the nuclear membrane and the attachment of kinetochore microtubules to the tetrads. Unlike in mitosis, in which sister chromatids are pulled apart because each sister kinetochore is attached to a different pole, both sister kinetochores become attached to spindle microtubules coming from the same pole in metaphase I (fig. 3.23). During anaphase I, cohesin breaks down every place but at the centromeres, allowing sister chromatids to be pulled to



(a)

(b)

Figure 3.22 (*a*) Recombination nodules (*arrowhead*) in spermatocytes of the pigeon, *Columba livia.* (Bar = 1 μm.) (*b*) A tetrad from the grasshopper, *Chorthippus parallelus,* at diplonema with five chiasmata. ([a] From M. I. Pigozzi and A. J. Solari, "Recombination Nodule Mapping and Chiasma Distribution in Spermatocytes of the Pigeon, *Columba livia,*" in *Genome,* 42: 308–314, 1999. Reprinted by permission. [b] Courtesy of Bernard John.)

the same pole: homologous chromosomes are separated (fig. 3.24). This meiotic division is therefore called a **reductional division** because it reduces the number of chromosomes to half the diploid number in each daughter cell. For every tetrad there is now one chromosome in the form of a chromatid pair, known as a **dyad** or **monovalent,** at each pole of the cell. The initial objective of meiosis, separating homologues into different daughter cells, is accomplished. However, since each dyad consists of two sister chromatids, a second, mitosis-like division is required to reduce each chromosome to a single chromatid.

Telophase I and Prophase II

Depending on the organism, telophase I may or may not be greatly shortened in time. In some organisms, all the expected stages take place; chromosomes enter an interphase configuration as cytokinesis takes place. However, no chromosome duplication (DNA replication) occurs during this abbreviated interphase, termed **interkinesis.** Next, in these organisms, prophase II begins and

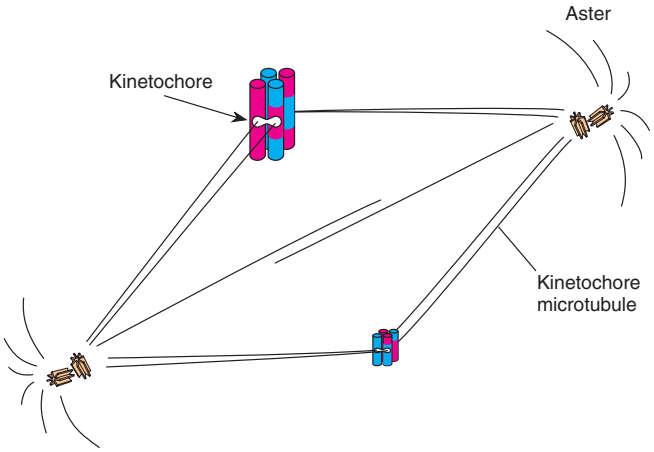
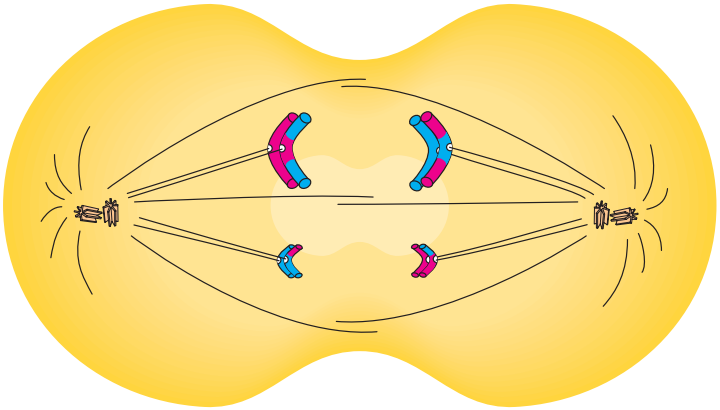


Figure 3.23 Metaphase of meiosis I; $2n = 4$. Maternal chromosomes are *red;* paternal chromosomes are *blue.* Sister kinetochores (effectively single, merged kinetochores) are attached to microtubules from the same pole.



Anaphase I

Figure 3.24 Anaphase of meiosis I; $2n = 4$. Maternal chromosomes are *red;* paternal chromosomes are *blue.* Homologous chromosomes separate and move to opposite poles.

meiosis II proceeds. In still other organisms, the late anaphase I chromosomes go almost directly into metaphase II, virtually skipping telophase I, interphase, and prophase II.

Meiosis II

Meiosis II is basically a mitotic division in which the chromatids of each chromosome are pulled to opposite poles. For each original cell entering meiosis I, four cells emerge at telophase II. Meiosis II is an **equational division;** although it reduces the amount of genetic material per cell by half, it does not further reduce the chromosome number per cell (fig. 3.25). (Sometimes it is simpler to concentrate on the behavior of centromeres during meiosis than on the chromosomes and chromatids. Meiosis I separates maternal from paternal centromeres, and meiosis II separates sister centromeres.) Figure 3.26 summarizes meiosis in corn (*Zea mays*).

In terms of chromosomes, meiosis begins with a diploid cell and produces four haploid cells. In terms of DNA, the process is a bit more complex but has the same

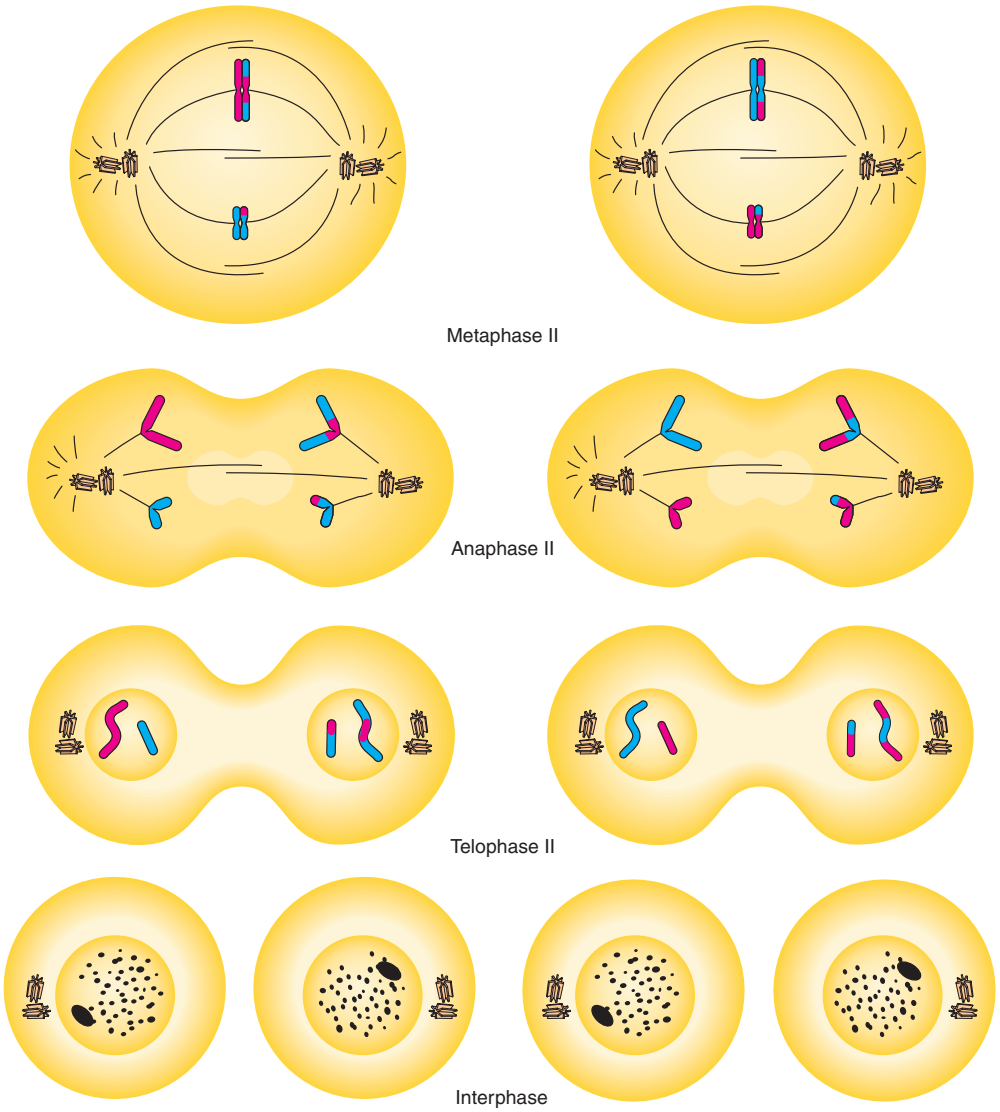


Figure 3.25 Meiosis II; $2n = 4$. Maternal chromosomes are *red;* paternal chromosomes are *blue.*

result. Let us call the quantity of DNA in a gamete "C." A diploid cell before S phase has 2C DNA, and the same cell after S phase, but before mitosis, has 4C DNA. Mitosis reduces the quantity of DNA to 2C. A cell entering meiosis also has 4C DNA. After the first meiotic division, each daughter cell has 2C DNA, and after the second meiotic division, each daughter cell has C DNA, the quantity appropriate for a gamete.

The Significance of Meiosis

Meiosis is significant for several reasons. First, it reduces the diploid number of chromosomes so that each of four daughter cells has one complete haploid chromosome set. Second, because of the randomness of the process of chromosomal separation, a very large number of different chromosomal combinations can form in the gametes. For example, in human beings, if each gamete could get either the maternal or paternal chromosome, and we have twenty-three chromosomal pairs, 2^{23} or 8,388,608 different combinations can occur. Third, because of crossing over, even more allelic combinations are possible. The process of creating new arrangements, either by crossing over or by independent segregation of homologous pairs of chromosomes, is called **recombination.** Assuming one hundred thousand genes in a human

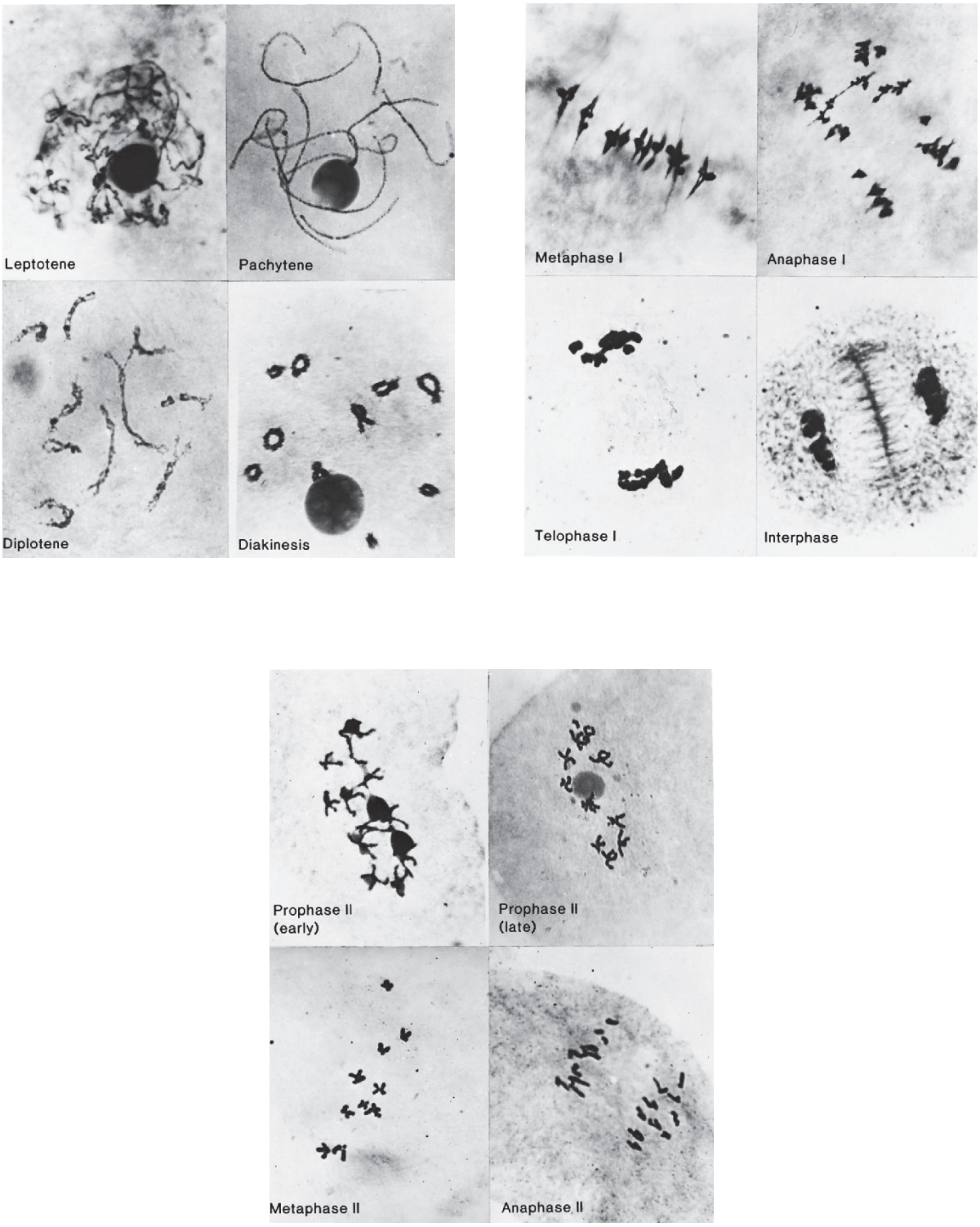


Figure 3.26 Meiosis in corn (*Zea mays*). (Courtesy of Dr. M. M. Rhoades. "Meiosis in maize," *Journal of Heredity*, 41: 59–67, 1950. Reproduced by permission.)

being with two alleles each, $2^{100,000}$ different gametes could potentially arise by meiosis.

The behavior of any tetrad follows the pattern of Mendel's rule of segregation. At spore or gamete formation (meiosis), the diploid number of chromosomes is halved; each gamete receives only one chromosome from a homologous pair. This process, of course, explains Mendel's rule of segregation. Chromosomal behavior at meiosis also explains independent assortment (fig. 3.27). In anaphase I, the direction of separation is independent in different tetrads. Whereas one pole may get the maternal centromere from chromosomal pair number 1, it could get either the maternal or the paternal centromere from chromosomal pair number 2, and so on (see fig. 3.27). Alleles of one gene segregate independently of alleles of other genes. Very shortly after the rediscovery of Mendel's principles in 1900, geneticists were quick to realize this.

MEIOSIS IN ANIMALS

In male animals, each meiosis produces four equal-sized **sperm cells** in a process called **spermatogenesis** (fig. 3.28). In vertebrates, a cell type in the testes known as a **spermatogonium** produces **primary spermatocytes,** as well as additional spermatogonia, by mitosis.

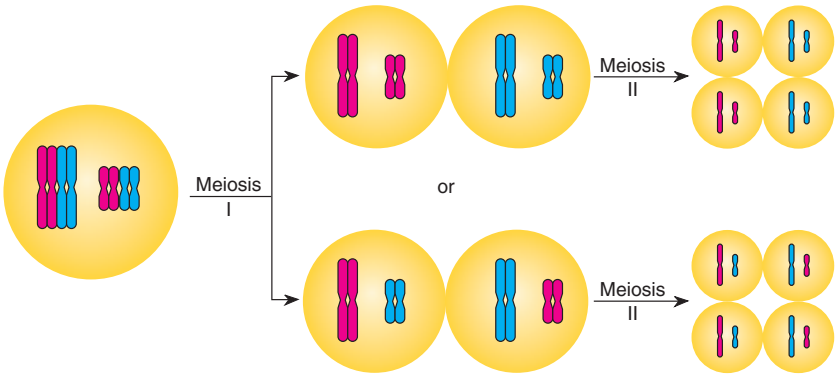


Figure 3.27 Relationship of meiosis to the rule of independent assortment. Maternal (*red*) and paternal (*blue*) chromosomes separate independently in different tetrads.

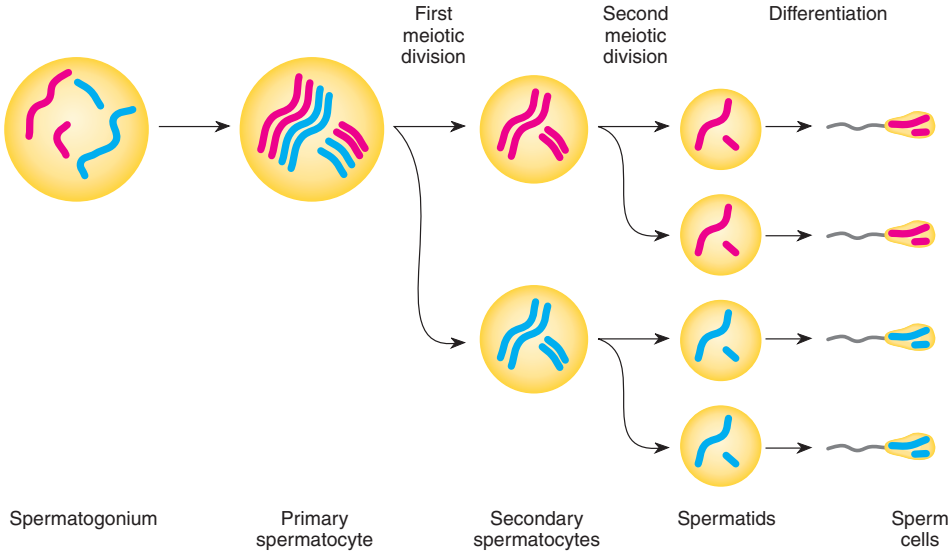


Figure 3.28 Spermatogenesis; $2n = 4$. Maternal chromosomes are *red;* paternal chromosomes are *blue.*

The primary spermatocytes then undergo meiosis. After the first meiotic division, these cells are known as **secondary spermatocytes;** after the second meiotic division, they are known as **spermatids.** The spermatids mature into spermatozoa by a process called **spermiogenesis**—with four sperm cells resulting from each primary spermatocyte. In human beings and other vertebrates without a specific mating season, the process of spermatogenesis is continuous throughout adult life. A normal human male may produce several hundred million sperm cells per day.

During embryonic development in human females, cells in the ovary, known as **oogonia,** proliferate by numerous mitotic divisions to form **primary oocytes.** About one million form per ovary. These begin the first meiotic division and then stop before the birth of the female in a prolonged diplonema, called the **dictyotene** stage. A primary oocyte does not resume meiosis until the female is past puberty, when, under hormonal control, ovulation takes place. This process usually occurs for only one oocyte per month during the female's reproductive life span (from about twelve to fifty years of age). Meiosis only then proceeds in the ovulated oocyte. In the female, the two cells formed by meiosis I are of unequal size. One, termed the **secondary oocyte,** contains almost all the nutrient-rich cytoplasm; the other, a **polar body,** receives very little cytoplasm. The second meiotic division in the larger cell yields another polar body and an **ovum.** The first polar body may or may not divide to form two other polar bodies, which ultimately disintegrate. Thus, **oogenesis** produces cells of unequal size—an ovum and two or three polar bodies (fig. 3.29). Cells of unequal size are produced because the oocyte nucleus and meiotic spindle reside very close to the surface of this large cell.

LIFE CYCLES

For eukaryotes, the basic pattern of the life cycle alternates between a diploid and a haploid state (see fig. 3.1). With the exception of the life cycles of bacteria and viruses, all life cycles are modifications of this general pattern. Bacteria, including blue-green algae, have a single circular chromosome; with exceptions described later, they are always in the haploid state. They divide by replicating their DNA and having the two copies separate into two daughter cells by simple cell division (see chapter 7). Viruses, on the border of being called alive, insert their genetic material into the cells of other organisms, and then manufacture new copies of themselves (see chapter 7).

Most animals are diploids that form gametes by meiosis, then restore the diploid number by fertilization. Exceptions, however, are numerous. For example, in the bees, wasps, and ants (hymenoptera), males are haploid and produce gametes by mitosis; females are diploid. Some fishes exist by **parthenogenesis,** in which the offspring come from unfertilized eggs that do not undergo meiosis. And, in some copepods, the sexual and parthenogenetic stages of their life cycles alternate.

The general pattern of the life cycle of plants alternates between two distinct generations, each of which, depending on the species, may exist independently. In lower plants, the haploid generation predominates, whereas in higher plants, the diploid generation is dominant. In flowering plants **(angiosperms),** the plant you see is the diploid **sporophyte** (see fig. 3.1). It is referred to as a sporophyte because, through meiosis, it will give rise to spores. The spores germinate into the alternate generation, the haploid **gametophyte,** which produces gametes by mitosis. Fertilization then produces the next generation

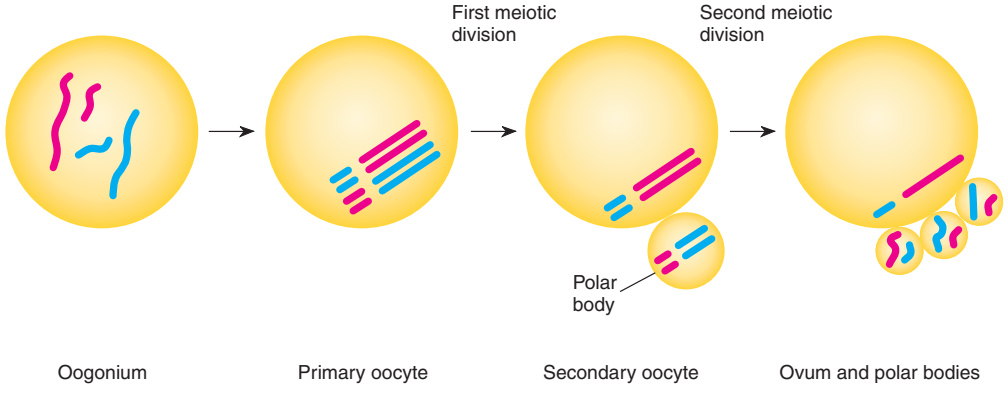


Figure 3.29 Oogenesis; $2n = 4$. Maternal chromosomes are *red;* paternal chromosomes are *blue.*

of diploid sporophytes. In lower plants, the gametophyte has an independent existence; in angiosperms, this generation is radically reduced. For example, in corn (fig. 3.30), an angiosperm, the mature corn plant is the sporophyte. The male flowers produce microspores by meiosis. After mitosis, three cells exist in each spore, a structure that we call a **pollen grain,** the male gametophyte. In female flowers, meiosis produces megaspores. Mitosis within a megaspore produces an embryo sac of seven cells with eight nuclei. This is the female gametophyte. A sperm cell fertilizes the egg cell. The two polar nuclei of the embryo sac are fertilized by a second sperm cell, producing triploid ($3n$) nutritive endosperm tissue. The sporophyte grows from the diploid fertilized egg.

Many fungi and protista are haploid. Fertilization produces a diploid stage, which almost immediately undergoes meiosis to form haploid cells. These cells, in turn, increase in number by mitosis. We will analyze organisms such as *Neurospora,* the pink bread mold, in more detail later (see chapter 6).

Much of our knowledge of genetics derives from the study of specific organisms with unique properties. Mendel found pea plants useful because he could control matings carefully, their generation time was only a year, he could easily grow them in his garden, and they had the discrete traits that he was seeking. Our interest in human beings is obvious. However, we are members of a very difficult species to study experimentally. We have a long generation time and a small number of offspring from matings that we cannot tailor for research purposes. The fruit fly, *Drosophila melanogaster,* is one of the organisms geneticists have studied most extensively. Fruit flies have a short generation time (twelve to fourteen days), which means that many matings can be carried out in a reasonable amount of time. In addition, they do exceptionally well in the laboratory, they have many easily observable mutants, and in several organs they have giant banded chromosomes of great interest to cytogeneticists.

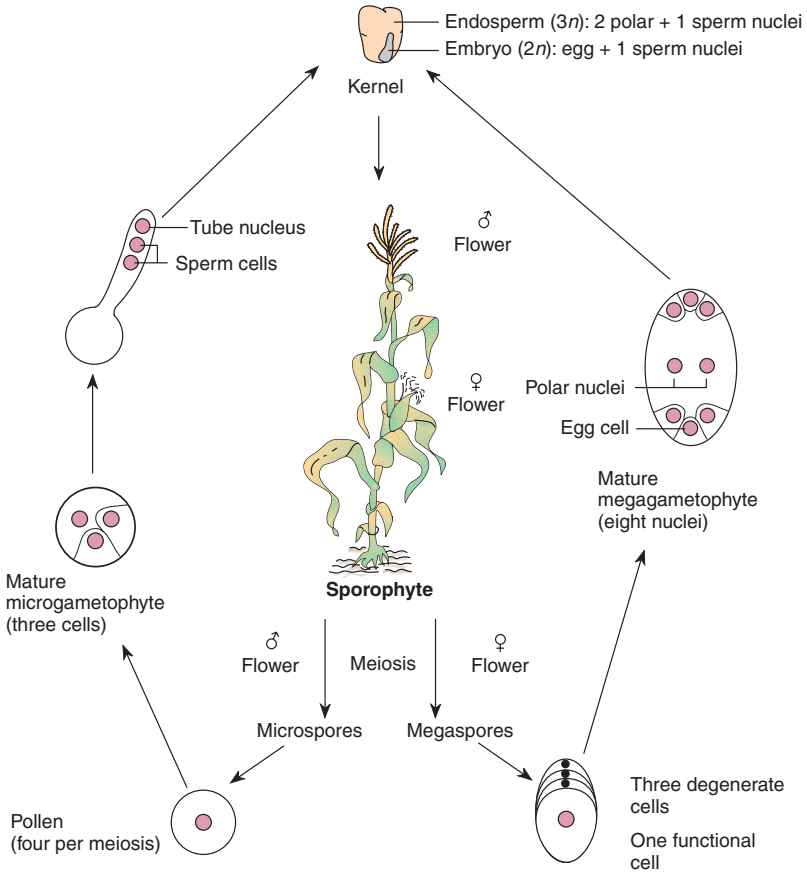


Figure 3.30 Life cycle of the corn plant.

Note that species used in food production tend to be intermediate in their life cycles. That is, many crop plants, such as peas and corn, have only one generation interval per year under normal circumstances. (We use the term *generation interval* here in the broadest sense, as the time it takes to complete an entire life cycle; see also chapter 19.) Crop plants are easier to work with from a genetic standpoint than people, but much more difficult than, say, *Drosophila* or bacteria (table 3.4). Because of their relatively long generation interval, crop plants are limited in their utility for studying basic genetic concepts or applying genetic technology to agriculture.

As you make your way through this book and through other readings on genetics, and as you come across studies involving new organisms, ask yourself the question, What are the properties of this organism that make it ideal for this type of research?

CHROMOSOMAL THEORY OF HEREDITY

In a paper in 1903, cytologist Walter Sutton firmly stated the concepts we have developed here: The behavior of chromosomes during meiosis explains Mendel's principles. Genes, then, must be located on chromosomes. This idea, which several other biologists were also developing at the time, was immediately accepted, ushering in the era of the **chromosomal theory of inheritance.** During this era, intensive effort was devoted to studying the relationships between genes and chromosomes. The major portion of the first section of this book is devoted to classical studies of **linkage** and **mapping.** Linkage deals with the association of genes to each other and to specific chromosomes. Mapping deals with the sequence of genes on a chromosome and the distances between genes on the same chromosome. This is basic information for a study of the structure and function of genes. Here we introduce a new term for the gene. The term **locus** (plural: *loci*), meaning "place" in Latin, refers to the location of a gene on the chromosome.

Table 3.4 Approximate Generation Intervals of Some Organisms of Genetic Interest

Organism	Approximate Generation Interval
Intestinal bacterium (*Escherichia coli*)	20 minutes
Bacterial virus (*lambda*)	1 hour
Pink bread mold (*Neurospora crassa*)	2 weeks
Fruit fly (*Drosophila melanogaster*)	2 weeks
House mouse (*Mus musculus*)	2 months
Corn (*Zea mays*)	6 months
Sheep (*Ovus aries*)	1 year
Cattle (*Bos taurus*)	2 years
Human being (*Homo sapiens*)	14 years

SUMMARY

STUDY OBJECTIVE 1: To observe the morphology of chromosomes 48–50

Chromosomes are made of chromatin and divided by centromeres. Within centromeres are kinetochores, attachment points for spindle fibers. Structure within the chromosomes is evident from bands on chromosomes called chromomeres.

STUDY OBJECTIVE 2: To understand the processes of mitosis and meiosis 50–61

During eukaryotic cell division, the processes of mitosis and meiosis apportion the chromosomes to daughter cells. Both processes are preceded by chromosome replication during the S phase of the cell cycle, which is under genetic control. In mitosis, the two sister chromatids making up each replicated chromosome separate into two daughter cells. Sex cells—gametes in animals and spores in plants—are produced by the two-stage process of meiosis. In meiosis, homologous chromosomes are first separated into two daughter cells, and then the sister chromatids making up each chromosome are distributed to two new daughter cells. We end up with four cells, each with the haploid chromosomal complement. The spindle is the apparatus that separates chromosomes in both mitosis and meiosis.

STUDY OBJECTIVE 3: To analyze the relationships between meiosis and Mendel's rules 61–65

The behavior of chromosomes during meiosis explains Mendel's two principles, segregation and independent assortment.

At the end of this chapter, we define the chromosomal theory of inheritance, the concept that shapes the first section of this book. This theory states that genes are located on chromosomes; their positions and order on the chromosomes can be discovered by mapping techniques described in later chapters.

SOLVED PROBLEMS

PROBLEM 1: What are the differences between chromosomes and chromatids?

Answer: In higher organisms, a chromosome is a linear DNA molecule complexed with protein and, generally, with a centromere somewhere along its length. During the cell cycle, in the S phase, the DNA replicates and each chromosome is duplicated. The duplication is visible in the early stages of mitosis and meiosis when chromosomes shorten. At this point, each duplicated chromosome is made up of two chromatids. The chromatids are called chromosomes when their centromeres are pulled to opposite poles of the spindle and each chromatid becomes independent.

PROBLEM 2: What are the relationships between mitosis and meiosis and Mendel's rules of segregation and independent assortment?

Answer: The process of mitosis does not relate directly to Mendel's rules. The behavior of chromosomes during meiosis, however, explains both segregation and independent assortment. Segregation is explained by the fact that only one chromosome from each homologous pair goes into a gamete; this is also true for the maternal and paternal alleles of a given gene. Independent assortment is explained by the independent behavior of each tetrad at meiosis. That is, the separation of maternal and paternal alleles in one tetrad is independent of the separation of maternal and paternal alleles in any other tetrad.

PROBLEM 3: A hypothetical organism has six chromosomes ($2n = 6$). How many different combinations of maternal and paternal chromosomes can appear in the gametes?

Answer: You could figure this empirically by listing all combinations. For example, let A, B, and C = maternal chromosomes and A′, B′, and C′ = paternal chromosomes. Two combinations in the gametes could be A B C′ and A′ B′ C; obviously, several other combinations exist. It is easier to recall that 2^n = number of combinations, where n = the number of chromosome pairs. In this case, $n = 3$, so we expect $2^3 = 8$ different combinations.

EXERCISES AND PROBLEMS*

CHROMOSOMES

1. What are the major differences between prokaryotes and eukaryotes?
2. What is the difference between a centromere and a kinetochore?
3. What is the difference between sister and nonsister chromatids? Between homologous and nonhomologous chromosomes?
4. In human beings, $2n = 46$. How many chromosomes would you find in a
   a. brain cell? **d.** sperm cell?
   b. red blood cell? **e.** secondary oocyte?
   c. polar body?
   (See also MEIOSIS IN ANIMALS)

MITOSIS

5. You are working with a species with $2n = 6$, in which one pair of chromosomes is telocentric, one pair subtelocentric, and one pair metacentric. The *A, B,* and *C* loci, each segregating a dominant and recessive allele (*A* and *a, B* and *b, C* and *c*), are each located on different chromosome pairs. Draw the stages of mitosis.
6. Identify stages *a–f* in the nuclear division shown in figure 1 (on the next page). Include the process, stage, and diploid number (e.g., meiosis I, prophase, $2n = 10$). Keep in mind that one picture could represent more than one process and stage. Chromosomes are drawn as threads, with circles representing kinetochores. (See also MEIOSIS)
7. When during the cell cycle does chromosome replication take place?
8. A mature human sperm cell has *c* amount of DNA. How much DNA (*c, 2c, 4c,* etc.) will a somatic cell have if it is in
   a. G_1?
   b. G_2?
   How much DNA will be in a cell at the end of meiosis I?

*Answers to selected exercises and problems are on page A-3.

MEIOSIS

9. Given the same information as in problem 5, diagram one of the possible meioses. How many different gametes can arise, absent crossing over? What variation in gamete genotype is introduced by a crossover between the *A* locus and its centromere?

10. How many bivalents, tetrads, and dyads would you find during meiosis in human beings? in fruit flies? in the other species of table 3.3?

11. Can you devise a method of chromosome partitioning during gamete formation that would not involve synapsis—that is, can you reengineer meiosis without passing through a synapsis stage?

12. What are the differences between a reductional and an equational division? What do these terms refer to?

13. How does the process of meiosis explain Mendel's two rules of inheritance?

14. *Drosophila* has four pairs of chromosomes. Let chromosomes from the male parent be A, B, C, and D, and those from the female parent be A′, B′, C′, and D′. What fraction of the gametes from an AA′ BB′ CC′ DD′ individual will be
a. all of paternal origin?
b. all of maternal origin?
c. half of maternal origin and half of paternal origin?

15. Wheat has $2n = 42$ and rye has $2n = 14$ chromosomes. Explain why a wheat-rye hybrid is usually sterile.

16. The arctic fox has fifty small chromosomes, and the red fox has thirty-eight larger chromosomes. Hybrids of these two species are sterile, but cytological studies during meiosis in these hybrids reveal both paired and unpaired chromosomes.
a. Account for the sterility of the hybrids.
b. How can you explain the paired chromosomes?

17. An organism has six pairs of chromosomes. In the absence of crossing over, how many different chromosomal combinations are possible in the gametes?

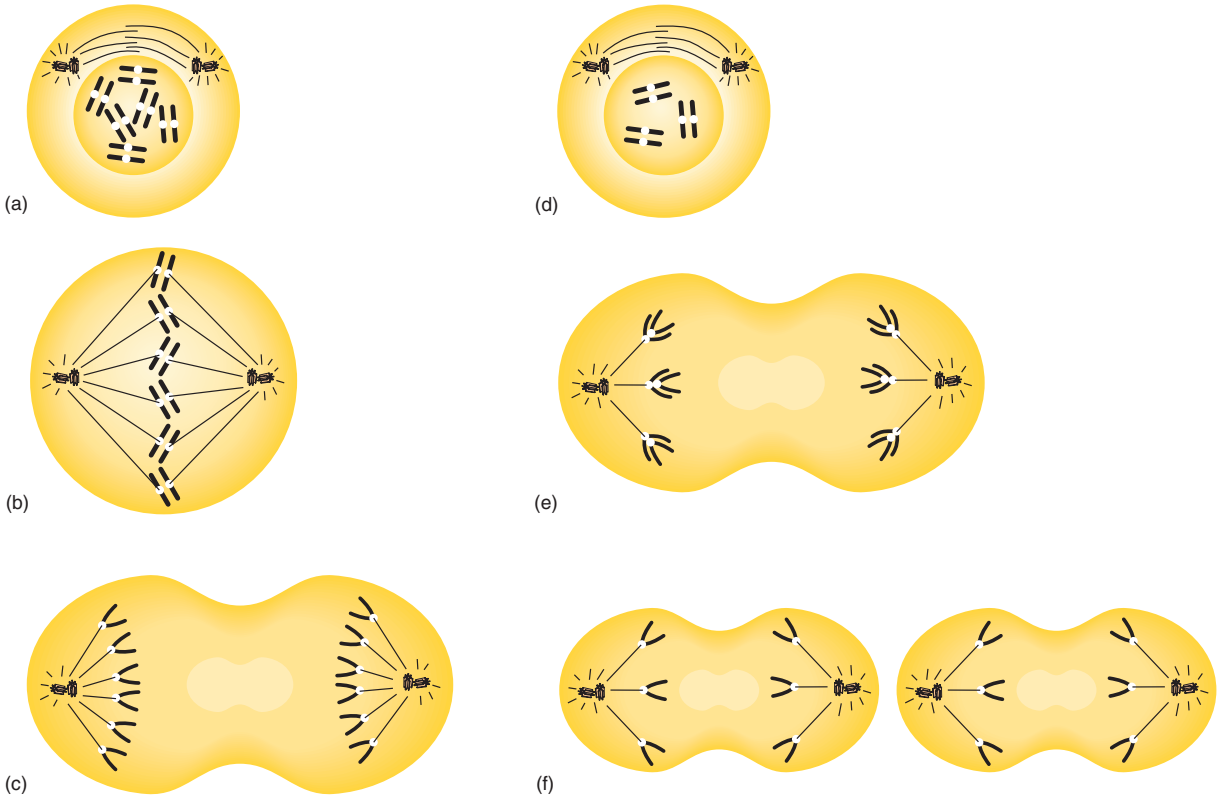


Figure 1 Stages in nuclear division.

MEIOSIS IN ANIMALS

18. How many sperm come from ten primary spermatocytes? How many ova from ten primary oocytes?

19. How do the quantity of genetic material and the ploidy change from stage to stage of spermatogenesis and oogenesis (see figs. 3.28 and 3.29)? (Consider the spermatogonium and the oogonium to be diploid, with the chromosome number arbitrarily set at two.)

20. How many sperm cells will form from
- **a.** fifty primary spermatocytes?
- **b.** fifty secondary spermatocytes?
- **c.** fifty spermatids?

21. In human beings, how many eggs will form from
- **a.** fifty primary oocytes?
- **b.** fifty secondary oocytes?

LIFE CYCLES

22. In corn (see fig. 3.30), the diploid number is twenty. How many chromosomes would you find in a(n)
- **a.** sporophyte leaf cell?
- **b.** embryo cell?
- **c.** endosperm cell?
- **d.** pollen grain?
- **e.** polar nucleus?

23. If a dihybrid corn plant is self-fertilized, what genotypes of the triploid endosperm can result? If you know the endosperm genotype, can you determine the genotype of the embryo?

24. Change the generalized life cycles of figure 3.1 so they describe the life cycles of human beings, peas, and *Neurospora.*

25. If the cytoplasm rather than nuclear genes controlled inheritance, what might be the relationship in phenotype and genotype between an organism and its parents in
- **a.** *Drosophila*?
- **b.** corn?
- **c.** *Neurospora*?

26. A drone (male) honeybee is haploid (arising from unfertilized eggs), and a queen (female) is diploid. Draw a testcross between a dihybrid queen and a drone. How many different kinds of sons and daughters might result from this cross?

27. The plant *Arabidopsis thaliana* has five pairs of chromosomes: AA, BB, CC, DD, and EE. If this plant is self-fertilized, what chromosome complement would be found in a root cell of the offspring?
- **a.** A B C D E
- **b.** AA BB CC DD EE
- **c.** AAA BBB CCC DDD EEE
- **d.** AAAA BBBB CCCC DDDD EEEE

28. In wheat, the haploid number is twenty-one. How many chromosomes would you expect to find in
- **a.** the tube nucleus?
- **b.** a leaf cell?
- **c.** the endosperm?

CHROMOSOMAL THEORY OF HEREDITY

29. A hypothetical organism has two distinct chromosomes ($2n = 4$) and fifty known genes, each with two alleles. If an individual is heterozygous at all known loci, how many gametes can be produced if
- **a.** all genes behave independently?
- **b.** all genes are completely linked?

CRITICAL THINKING QUESTIONS

1. Can meiosis occur in a haploid cell? can mitosis?

2. What is the minimum number of chromosomes that an organism can have? the maximum number?

Suggested Readings for chapter 3 are on page B-1.