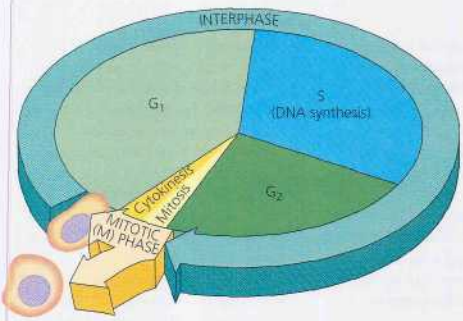
Concept 12.2

The mitotic phase alternates with interphase in the cell cycle

Ir. 1882, a German anatomist named Walther Flemming devc loped dyes that allowed him to observe, for the hrst Lime, ttje behavior of chromosomes during mitosis and cytokinesis. (In fact, Flemming coined the terms *mitosis* and *chromatin.)* During the period between one cell division and the next, it appeared to Flemming that the cell was simply growing larger. But we now know that many critical events occur during this st age in the life of a cell.

Phases of the Cell Cycle

Mitosis is just one part of the cell cycle **(Figure 12.5).** In fact, the m itotic (M) phase, which includes both mitosis and cytokinesis, is usually the shortest part of the cell cycle. Mitotic cell division alternates with a much longer stage called interphase, which often accounts for about 90% of the cycle. His during interphase that the cell grows and copies its chromosomes in preparation for cell division. Interphase can be divided "into sabphases: the Gj phase ("first gap"), the S phase ("synthesis"), and the G2 phase ("second gap"). During all three subphases, the cell grows by producing proteins and cytoplasmic organelles such as mitochondria and endoplasmic reticulum. Lowever, chromosomes are duplicated only during the S phase (ve discuss synthesis of DNA in Chapter 16). Thus, a cell grows (G_1), continues to grow as it copies its chromosomes (S), grows rlore as it completes preparations for cell division (G_2), and di- Ldes (M). The daughter cells may then repeat the cycle.



k **Figure 12.5 The cell cycle.** In a dividing cell, the mitotic (M) •hase alternates with interphase, a growth period. The first part of nterphase, called G,, is followed by the S phase, when the hromosomes replicate; the last part of interphase is called G_2. In the vl phase, mitosis divides the nucleus and distributes its chromosomes 0 the daughter nuclei, and cytokinesis divides the cytoplasm, >roducing two daughter cells.

A typical human cell might undergo one division in 24 hours. Of this time, the M phase would occupy less than 1 hour, while the S phase might occupy about 10-12 hours, or about half the cycle. The rest of the Lime would be apportioned between the *Gi* and G_2 phases. The G_2 phase usually takes 4-6 hours; in our example, Gj would occupy about 5-6 hours. Gi is the most variable in length in different types of cells.

Time-lapse films of living, dividing cells reveal the dynamics of mitosis as a continuum of changes. For purposes of description, however, mitosis is conventionally broken down into five stages: prophase, prometaphase, metaphase, anaphase, and telophase. Overlapping with the latter stages of mitosis, cytokinesis completes the mitotic phase. **Figure 12.6,** on the next two pages, describes these stages in an animal cell. Be sure to study this figure thoroughly before progressing to the next two sections, which examine mitosis and cytokinesis more closely.

The Mitotic Spindle: *A Closer Look*

Many of the events of mitosis depend on the mitotic spindle, which begins to form in the cytoplasm during prophase. This structure consists of fibers made of microtubules and associated proteins. While the mitotic spindle assembles, the other microtubules of the cytoskeleton partially disassemble, probably providing the material used to construct the spindle. The spindle microtubules elongate by incorporating more subunits of the protein tubulin (see Table 6.1).

The assembly of spindle microtubules starts at the centrosome, a nonmembranous organelle that functions throughout the cell cycle to organize the cell's microtubules (it is also called the *microtubule-organizing center).* In animal cells, a pair of centrioles is located at the center of the centrosome, but the centrioles are not essential for cell division, in fact, the centrosomes of most plants lack centrioles, and if the centrioles of an animal cell are destroyed with a laser rnicrobeam, a spindle nevertheless forms during mitosis.

During interphase, the single centrosome replicates, forming two centrosomes, which remain together near the nucleus (see Figure 12.6). The two centrosomes move apart from each other during prophase and prometaphase of mitosis, as spindle microtubules grow out from them. By the end of prometaphase, the two centrosomes, one at each pole of the spindle, are at opposite ends of the cell. An aster, a radial array of short microtubules, extends from each centrosome. The spindle includes the centrosomes, the spindle microtubules, and the asters.

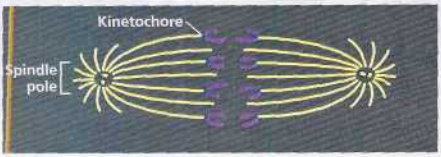
Each of the two sister chromatids of a chromosome has a kinetochore, a structure of proteins associated with specific sections of chromosomal DNA at the centromere. The chromosome's two kinetochores face in opposite directions. During prometaphase, some of the spindle microtubules attach to the kinetochores; these are called kinetochore microtubules. (The number of microtubules attached to a kinetochore varies

Figure 12.8

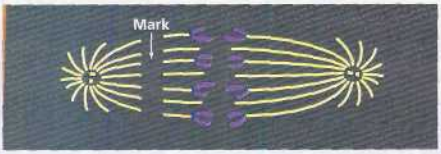
Inquiry During anaphase, do kinetochore microtubules shorten at their spindle pole ends or their kinetochore ends?

EXPERIMENT

1 The microtubules of a cell in early anaphase were labeled with a fluorescent dye that glows in the microscope (yellow).

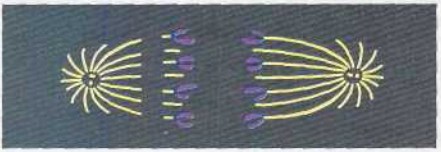


2 A laser was used to mark the kinetochore microtubules by eliminating the fluorescence in a region between one spindle pole and the chromosomes. As anaphase proceeded, researchers monitored the changes in the lengths of the microtubules on either side of the mark.



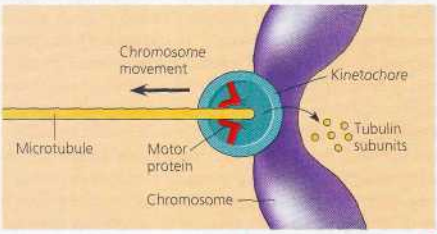
RESULTS

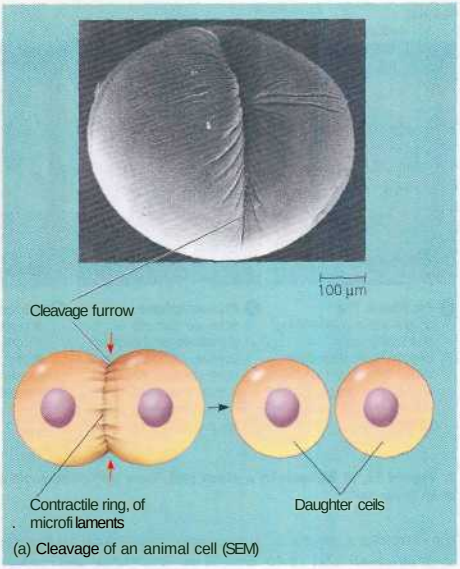
As the chromosomes moved toward the poles, the microtubule segments on the kinetochore side of the laser mark shortened, while those on the spindle pole side stayed the same length.



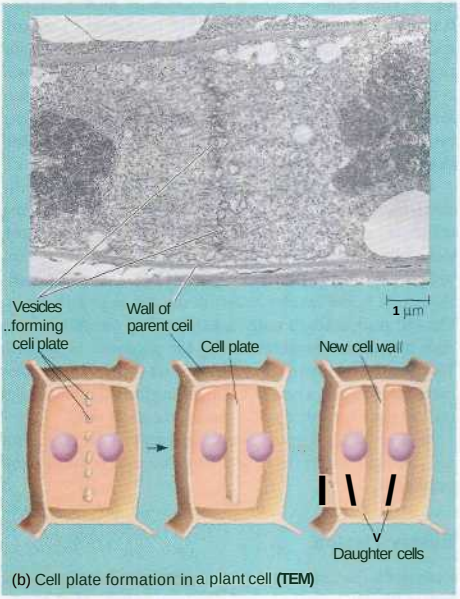
CONCLUSION

This experiment demonstrated that during anaphase, kinetochore microtubules shorten at their kinetochore ends, not at their spindle pole ends. This is just one of the experiments supporting the hypothesis that during anaphase, a chromosome tracks along a microtubule as the microtubule depolymerizes at its kinetochore end, releasing tubulin subunits.



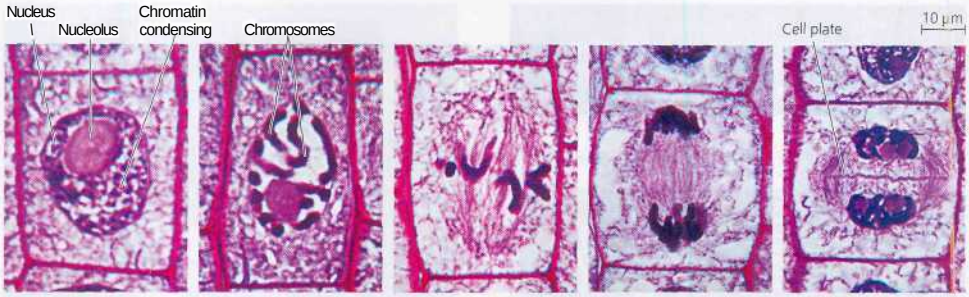


(a) Cleavage of an animal cell (SEM)



(b) Cell plate formation in a plant cell (TEM)

Figure 12.9 Cytokinesis in animal and plant cells.



0 Prophase. The chromatin is condensing. The nucleolus is beginning to disappear. Although not yet visible in the micrograph, the mitotic spindle is starting to form.

2 Prometaphase. We now see discrete chromosomes; each consists of two identical sister chromatids. Later in prometaphase, the nuclear envelope will fragment.

0 Metaphase. The spindle is complete, and the chromosomes, attached to microtubules at their kinetochores, are all at the metaphase plate.

© Anaphase. The chromatids of each chromosome have separated, and the daughter chromosomes are moving to the ends of the cell as their kinetochore microtubules shorten,

0 Telophase. Daughter nuclei are forming. Meanwhile, cytokinesis has started; The cell plate, which will divide the cytoplasm in two, is growing toward the perimeter of the parent cell.

A Figure 12.10 Mitosis in a plant cell. These light micrographs show mitosis in cells of an onion root.

the furrow is a contractile ring of actin microfilaments associated with molecules of the protein myosin. (Actin and myosin are the same proteins that are responsible for muscle contraction as well as many other kinds of cell movement.) The actin microfilaments interact with the myosin molecules, causing the ring to contract. The contraction of the dividing cells ring of microfilaments is like the pulling of drawstrings. The cleavage furrow deepens until the parent cell is pinched in two, producing two completely separated cells, each with its own nucleus and share of cytosol and organelles.

Cytokinesis in plant cells, which have cell walls, is markedly different. There is no cleavage furrow. Instead, during telophase, vesicles derived from the Golgi apparatus move along microtubules to the middle of the cell, where they coalesce, producing a cell plate **(Figure 12.9b).** Cell wall materials carried in the vesicles collect in the cell plate as it grows. The cell plate enlarges until its surrounding membrane fuses with the plasma membrane along the perimeter of the cell. Two daughter cells result, each with its own plasma membrane. Meanwhile, a new cell wall arising from the contents of the cell plate has formed between the daughter cells.

Figure 12.10 is a series of micrographs of a dividing plant cell. Examining this figure will help you review mitosis and cytokinesis.

Binary Fission

Prokaryotes (bacteria) reproduce by a type of cell division called binary fission, meaning literally "division in half." Most bacterial genes are carried on a single *bacterial chromosome* that consists of a circular DNA molecule and associated proteins. Although bacteria are smaller and simpler than eukaryotic cells, the problem of replicating their genomes in an orderly fashion and distributing the copies equally to two daughter cells is still formidable. The chromosome of the bacterium *Escherichia coli*, for example, when it is fully stretched out, is about 500 times longer than the length of the cell. Clearly, such a long chromosome must be highly coiled and folded within the cell—and it is.

In E. *coli*, the process of cell division begins when the DNA of the bacterial chromosome begins to replicate at a specific place on the chromosome called the origin of replication, producing two origins. As the chromosome continues to replicate, one origin moves rapidly toward the opposite end of the cell **(Figure 12.11).** While the chromosome is replicating, the cell elongates. When replication is complete and the bacterium has reached about twice its initial size, its plasma membrane grows inward, dividing the parent *E. coli* cell into two daughter cells. Each cell inherits a complete genome.

Using the techniques of modern DNA technology to tag the origins of replication with molecules that glow green in fluorescence microscopy (see Figure 6.3), researchers have directly observed the movement of bacterial chromosomes. This movement is reminiscent of the poleward movements of the centromere regions of eukaryotic chromosomes during anaphase of mitosis, but bacteria don't have visible mitotic spindles or even microtubules. In most bacterial species studied, the two origins of replication end up at opposite ends of the cell or in some other very specific location, possibly anchored there by one or more proteins. How bacterial chromosomes move and how their specific location is established and maintained are

resut: Each cycle of chromosome halving and doubling contributes to genetic variation among offspring. A closer look at meiosis will reveal the sources of this variation.

Concept Check 13.2

1. How does the karyotype of a human female differ from that of a human male?
2. How does the alternation of meiosis and fertilization in the life cycles of sexually reproducing organisms maintain the normal chromosome count for each species?
2. Dog sperm contain 39 chromosomes. What are the haploid number and diploid number for dogs?
4. What process (meiosis or mitosis) is more directly involved in the production of gametes in animals? In plants and most fungi?

For suggested answers, *see Appendix A.*

Concept 13.3

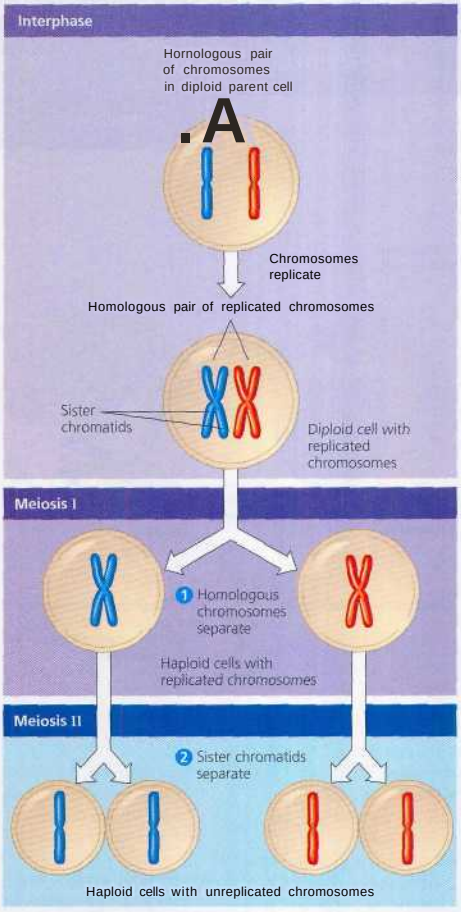
Meiosis reduces the number of diromosome sets from diploid to haploid

Many of the steps of meiosis closely resemble corresponding ste ps in mitosis. Meiosis, like mitosis, is preceded by the repliicai ion of chromosomes. However, this single replication is followed by two consecutive cell divisions, called meiosis **I** and **meiosis II.** These divisions result in four daughter cells (rather than the two daughter cells of mitosis), each with only hajlf as many chromosomes as the parent cell.

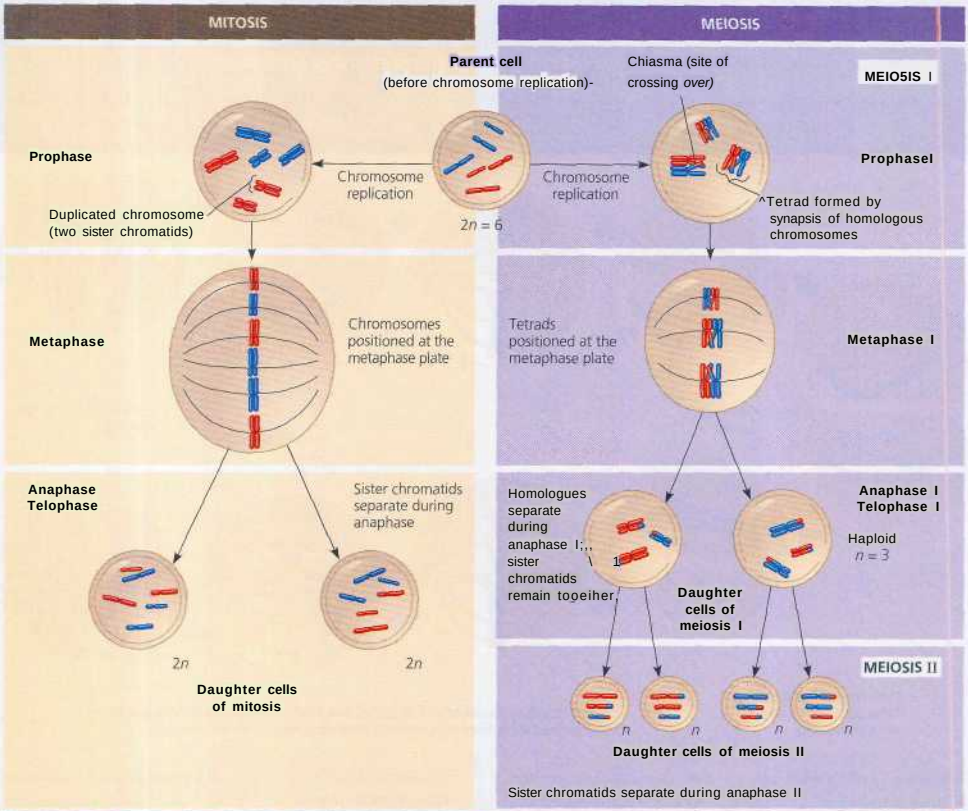
The Stages of Meiosis

Tike overview of meiosis in **Figure 13.7** shows how both members of a single homologous pair of chromosomes in a diploid cell are replicated and the copies then sorted into four haploid daughter cells. Recall that sister chromatids are two copies of *one* chromosome, attached at the centromere; together they mjake up one duplicated chromosome (see Figure 13.4). In contrast, the two chromosomes of a homologous pair are individual chromosomes that were inherited from different paremts; they are not usually connected to each other. Homologues appear alike in the microscope, but they may have different versions of genes at corresponding loci (for example, a gene fdir freckles on one chromosome and a gene for the absence of fijeckles at the same locus on the homologue).

Figure 13.8, on the next two pages, describes in detail the stages of the two divisions of meiosis for an animal cell whose diploid number is 6. Meiosis halves the total number of chromosomes in a very specific way reducing the number of sets from two to one, with each daughter cell receiving one set of chromosomes. Study Figure 13.8 thoroughly before going on to the next section.



***A* Figure 13.7 Overview of meiosis: how meiosis reduces chromosome number.** After the chromosomes replicate in interphase, the diploid cell divides *twice*, yielding four haploid daughter cells. This overview tracks just one pair of homologous chromosomes, which for the sake of simplicity are drawn in the condensed state throughout (they would not normally be condensed during interphase). The red chromosome was inherited from the female parent, the blue chromosome from the male parent.



SUMMARY

Property	Mitosis	Meiosis
DNA replication	Occurs during interphase before mitosis begins	Occurs during interphase before meiosis I begins
Number of divisions	One, including prophase, metaphase, anaphase, and telophase	Two, each including prophase, metaphase, anaphase, and telophase
Synapsis of homologous chromosomes	Does not occur	Occurs during prophase I, forming tetrads (groups of four chromatids); is associated with crossing over between non-sister chromatids
Number of daughter cells and genetic composition	Two, each diploid *(2n)* and genetically identical to the parent cell	Four, each hapfoid (n), containing half as many chromosomes as the parent cell; genetically different from the parent cell and from each other
Role in the animal body	Enables multicellular adult to arise from zygote; produces cells for growth and tissue repair	Produces gametes; reduces number of chromosomes by half and introduces genetic variability among the gametes

A Figure 13.9 A comparison of mitosis and meiosis.