CAMPBELL BIOLOGY IN FOCUS

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10

Meiosis and Sexual Life Cycles

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SECOND EDITION

Overview: Variations on a Theme

- Living organisms are distinguished by their ability to reproduce their own kind
- **Heredity** is the transmission of traits from one generation to the next
- **Variation** is demonstrated by the differences in appearance that offspring show from parents and siblings
- **Genetics** is the scientific study of heredity and variation

Figure 10.1

Concept 10.1: Offspring acquire genes from parents by inheriting chromosomes

- In a literal sense, children do not inherit particular physical traits from their parents

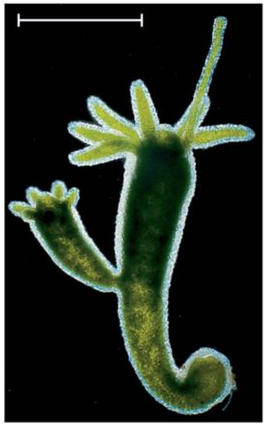
Inheritance of Genes

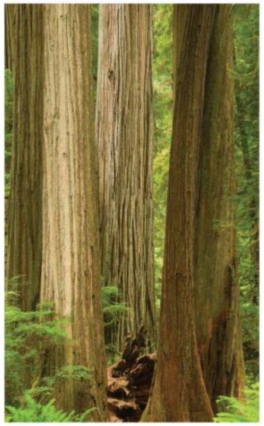
- **Genes** are the units of heredity and are made up of segments of DNA
- Genes are passed to the next generation via reproductive cells called **gametes** (sperm and eggs)

- Most DNA is packaged into chromosomes
- For example, humans have 46 chromosomes in their **somatic cells**, the cells of the body except for gametes and their precursors
- Each gene has a specific position, or **locus**, on a certain chromosome

Comparison of Asexual and Sexual Reproduction

- In **asexual reproduction**, a single individual passes genes to its offspring without the fusion of gametes
- A **clone** is a group of genetically identical individuals from the same parent
- In **sexual reproduction**, two parents give rise to offspring that have unique combinations of genes inherited from the two parents





Concept 10.2: Fertilization and meiosis alternate in sexual life cycles

- A **life cycle** is the generation-to-generation sequence of stages in the reproductive history of an organism

Sets of Chromosomes in Human Cells

- Human somatic cells have 23 pairs of chromosomes
- A **karyotype** is an ordered display of the pairs of chromosomes from a cell
- The two chromosomes in each pair are called **homologous chromosomes**, or **homologs**
- Chromosomes in a **homologous pair** are the same length and shape and carry genes controlling the same inherited characters

Figure 10.3

Technique

Results

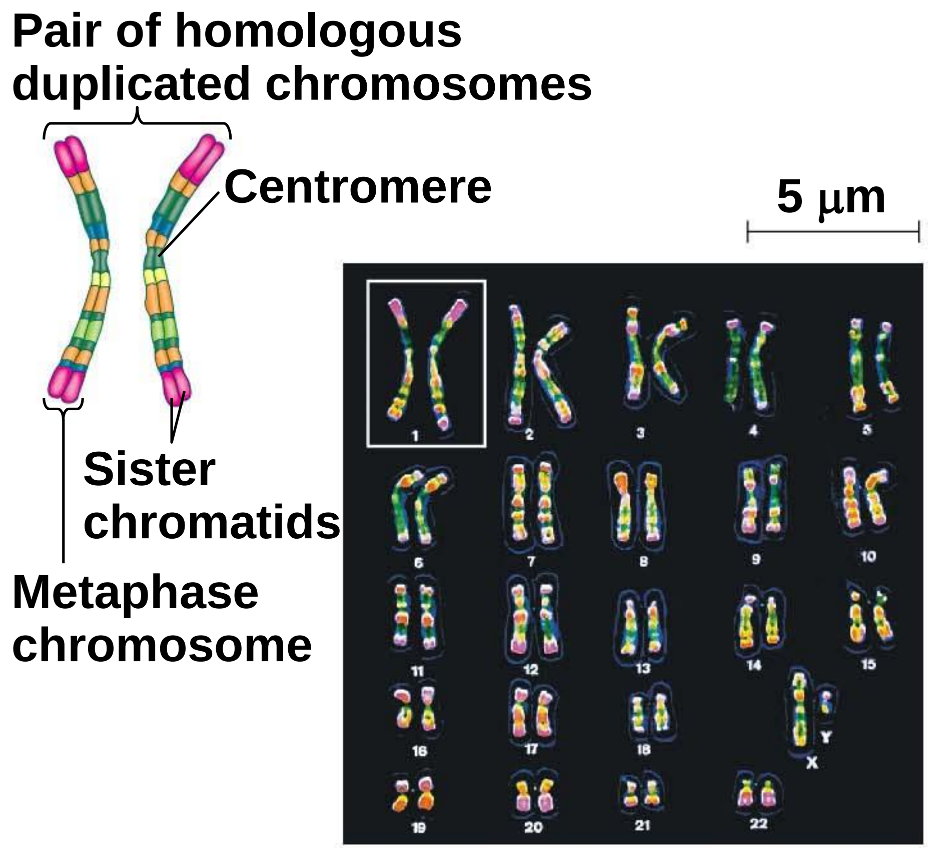
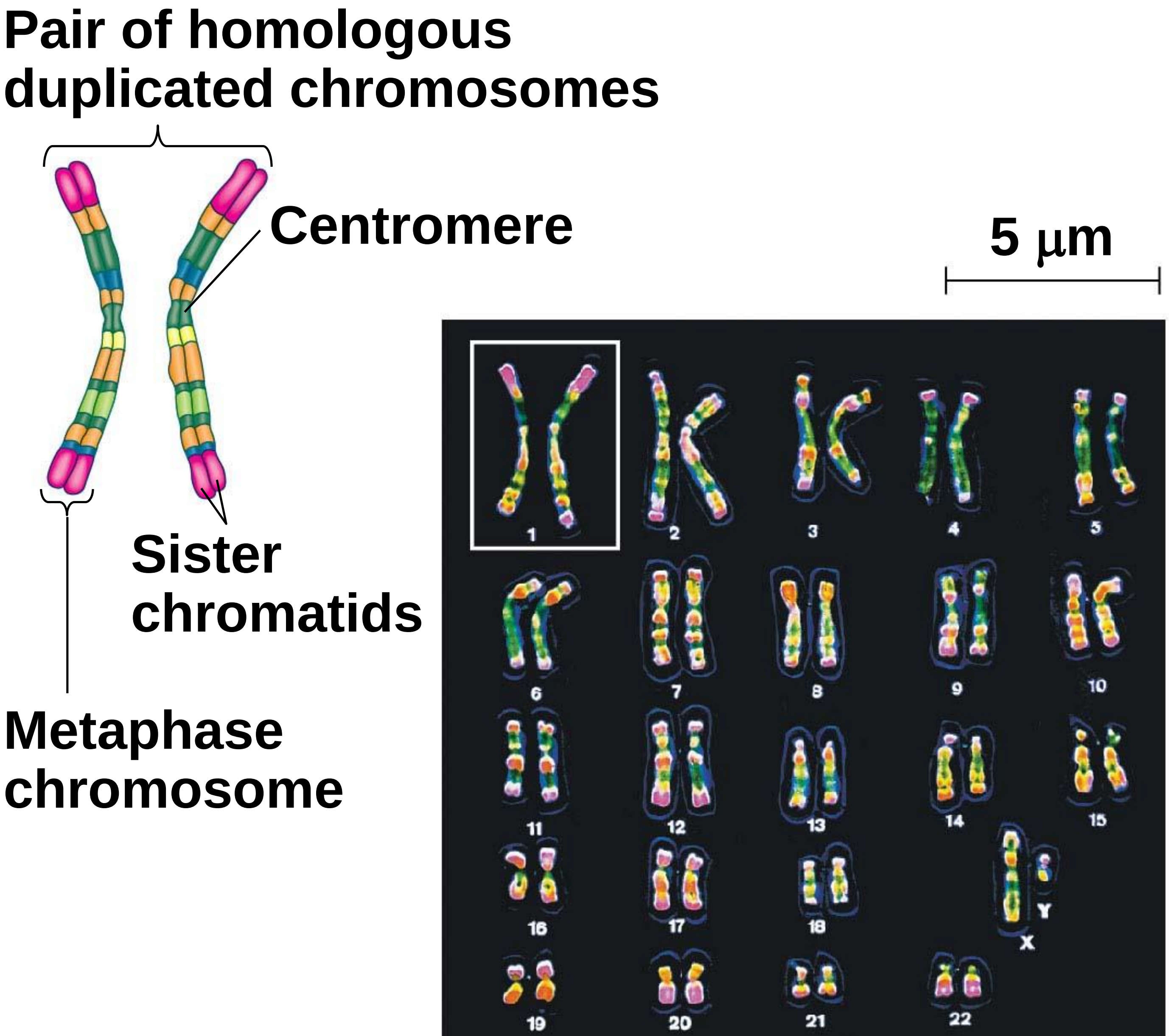


Figure 10.3-2

Results

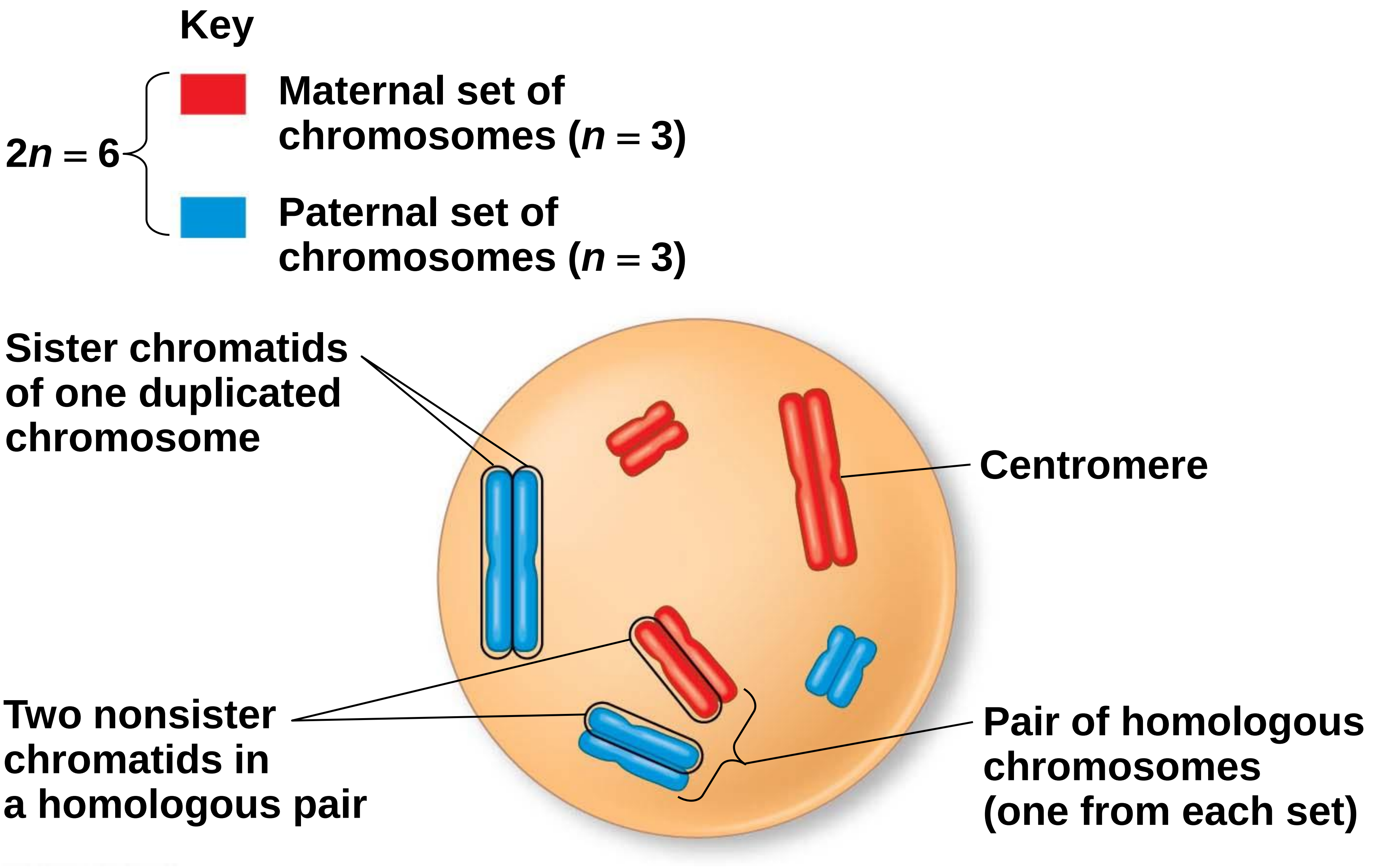


- The **sex chromosomes**, which determine the sex of the individual, are called X and Y
- Human females have a homologous pair of X chromosomes (XX)
- Human males have one X and one Y chromosome
- The remaining 22 pairs of chromosomes are called **autosomes**

- Each pair of homologous chromosomes includes one chromosome from each parent
- The 46 chromosomes in a human somatic cell are two sets of 23: one from the mother and one from the father
- A **diploid cell** (2*n*) has two sets of chromosomes
- For humans, the diploid number is 46 ($2n = 46$)

- In a cell in which DNA synthesis has occurred, each chromosome is replicated
- Each replicated chromosome consists of two identical sister chromatids

Figure 10.4



Key
Maternal set of chromosomes ($n = 3$)
Paternal set of chromosomes ($n = 3$)
$2n = 6$
Sister chromatids of one duplicated chromosome
Centromere
Two nonsister chromatids in a homologous pair
Pair of homologous chromosomes (one from each set)

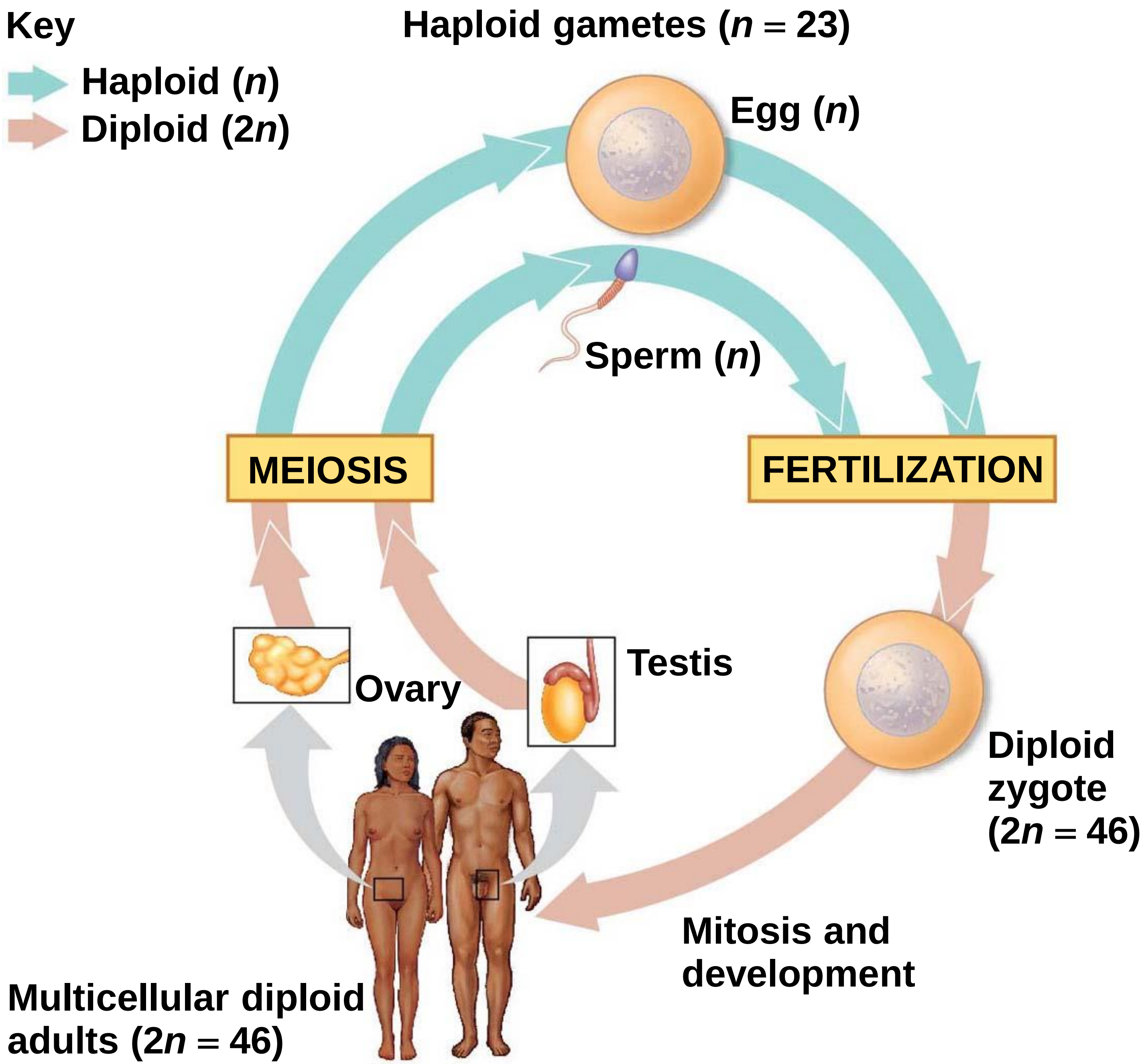
- A gamete (sperm or egg) contains a single set of chromosomes and is **haploid** (*n*)
- For humans, the haploid number is 23 ($n = 23$)
- Each set of 23 consists of 22 autosomes and a single sex chromosome
- In an unfertilized egg (ovum), the sex chromosome is X
- In a sperm cell, the sex chromosome may be either X or Y

Behavior of Chromosome Sets in the Human Life Cycle

- **Fertilization** is the union of gametes (the sperm and the egg)
- The fertilized egg is called a **zygote** and has one set of chromosomes from each parent
- The zygote produces somatic cells by mitosis and develops into an adult

- At sexual maturity, the ovaries and testes produce haploid gametes
- Gametes are the only types of human cells produced by **meiosis** rather than mitosis
- Meiosis results in one set of chromosomes in each gamete
- Fertilization and meiosis alternate in sexual life cycles to maintain chromosome number

Figure 10.5

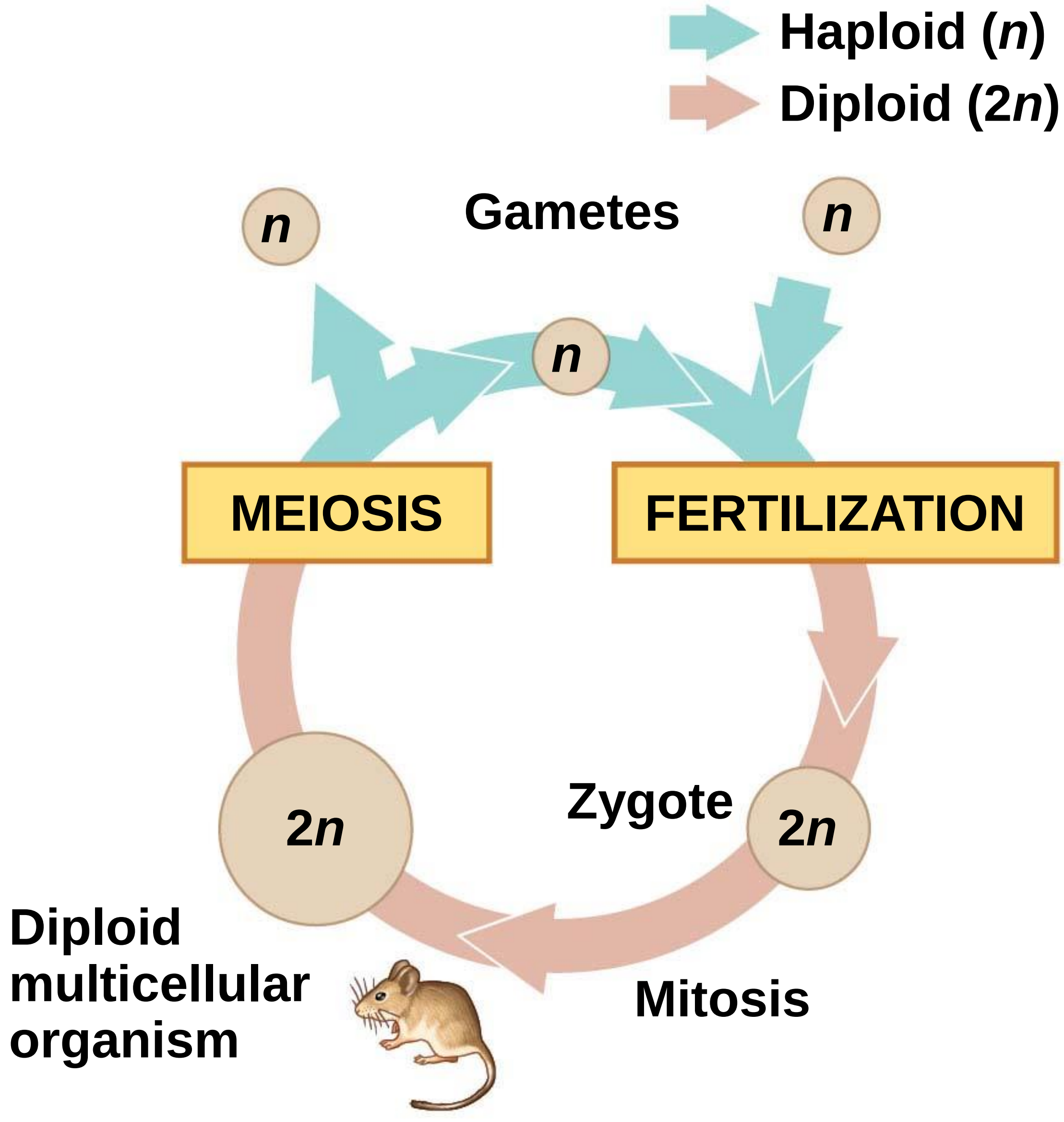

Key
Haploid (n)
Diploid (2n)
Haploid gametes (n = 23)
Egg (n)
Sperm (n)
MEIOSIS
FERTILIZATION
Ovary
Testis
Diploid zygote (2n = 46)
Mitosis and development
Multicellular diploid adults (2n = 46)

The Variety of Sexual Life Cycles

- The alternation of meiosis and fertilization is common to all organisms that reproduce sexually
- The three main types of sexual life cycles differ in the timing of meiosis and fertilization

- Gametes are the only haploid cells in animals
- They are produced by meiosis and undergo no further cell division before fertilization
- Gametes fuse to form a diploid zygote that divides by mitosis to develop into a multicellular organism

Figure 10.6-1

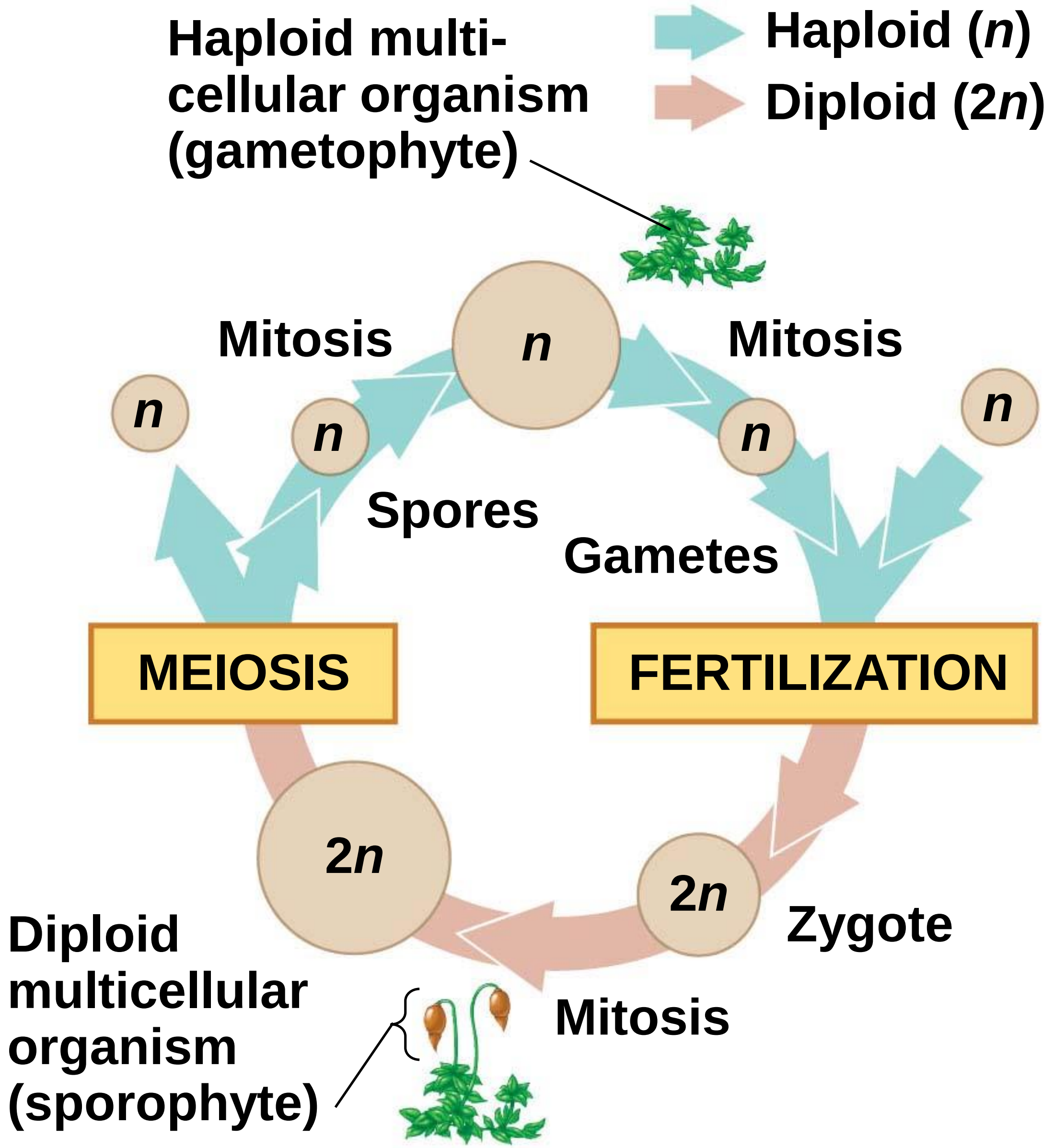


(a) Animals

- Plants and some algae exhibit an **alternation of generations**
- This life cycle includes both a diploid and haploid multicellular stage
- The diploid organism, called the sporophyte, makes haploid spores by meiosis

- Each spore grows by mitosis into a haploid organism called a gametophyte
- A gametophyte makes haploid gametes by mitosis
- Fertilization of gametes results in a diploid sporophyte

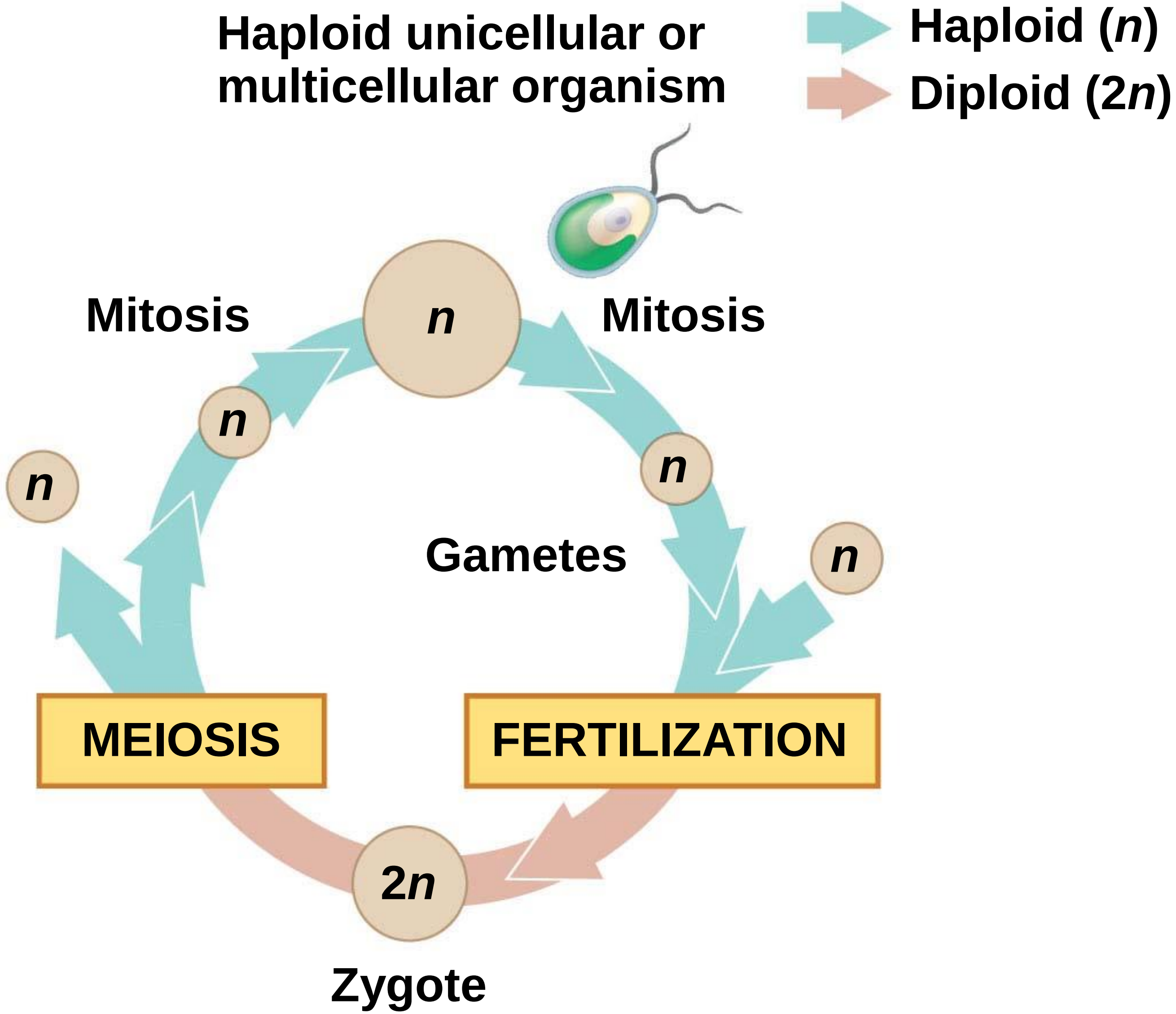
Figure 10.6-2



(b) Plants and some algae

- In most fungi and some protists, the only diploid stage is the single-celled zygote; there is no multicellular diploid stage
- The zygote produces haploid cells by meiosis
- Each haploid cell grows by mitosis into a haploid multicellular organism
- The haploid adult produces gametes by mitosis

Figure 10.6-3



(c) Most fungi and some protists

- Depending on the type of life cycle, either haploid or diploid cells can divide by mitosis
- However, only diploid cells can undergo meiosis
- In all three life cycles, the halving and doubling of chromosomes contribute to genetic variation in offspring

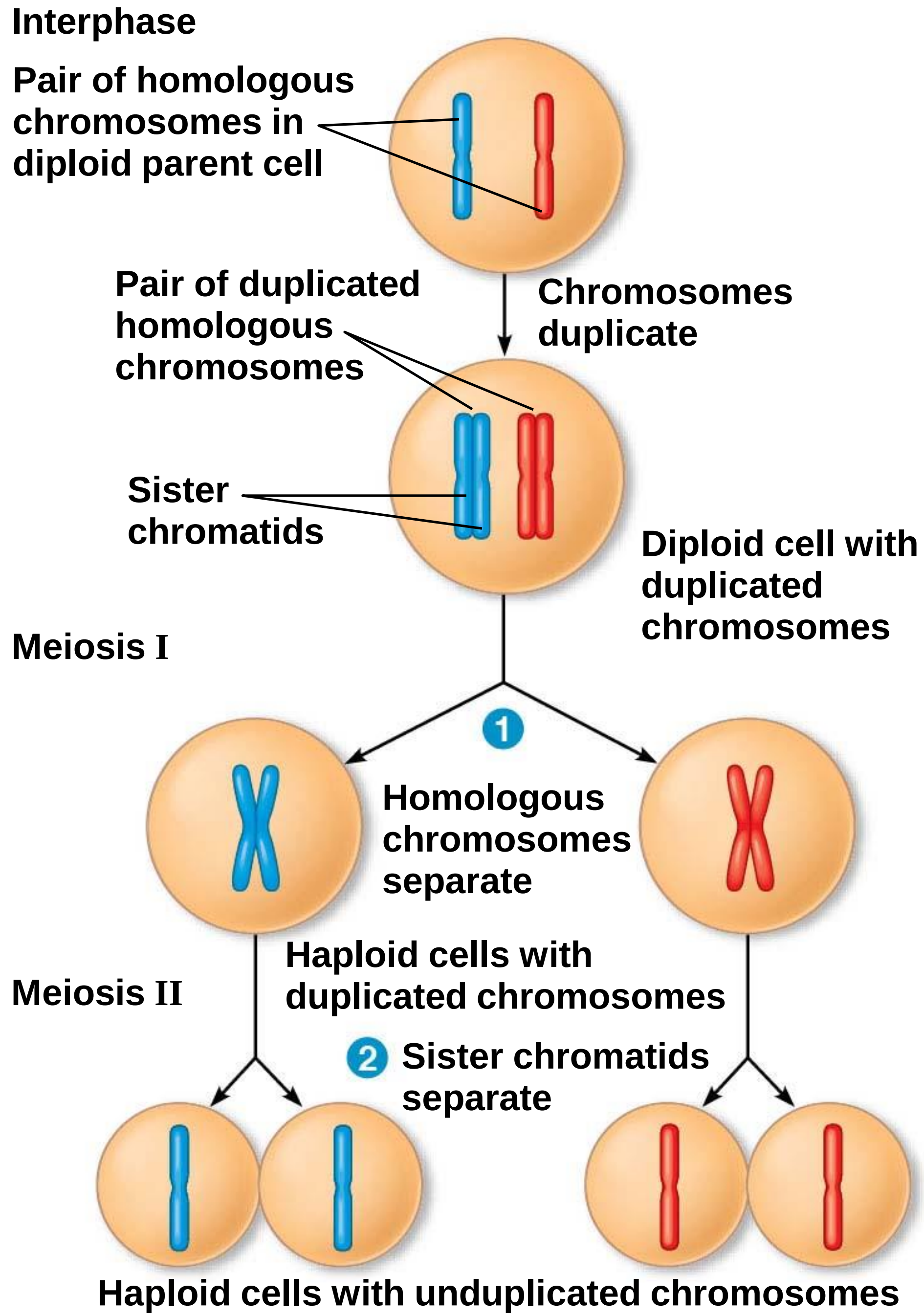
Concept 10.3: Meiosis reduces the number of chromosome sets from diploid to haploid

- Like mitosis, meiosis is preceded by the duplication of chromosomes
- Meiosis takes place in two sets of cell divisions, called **meiosis I** and **meiosis II**
- The two cell divisions result in four daughter cells, rather than the two daughter cells in mitosis
- Each daughter cell has only half as many chromosomes as the parent cell

The Stages of Meiosis

- For a single pair of homologous chromosomes in a diploid cell, both members of the pair are duplicated
- The resulting sister chromatids are closely associated all along their lengths
- Homologs may have different versions of genes, each called an allele
- Homologs are not associated in any obvious way except during meiosis

Figure 10.7


Interphase
Pair of homologous chromosomes in diploid parent cell
Chromosomes duplicate
Pair of duplicated homologous chromosomes
Sister chromatids
Diploid cell with duplicated chromosomes
Meiosis I
1
Homologous chromosomes separate
Haploid cells with duplicated chromosomes
Meiosis II
2
Sister chromatids separate
Haploid cells with unduplicated chromosomes

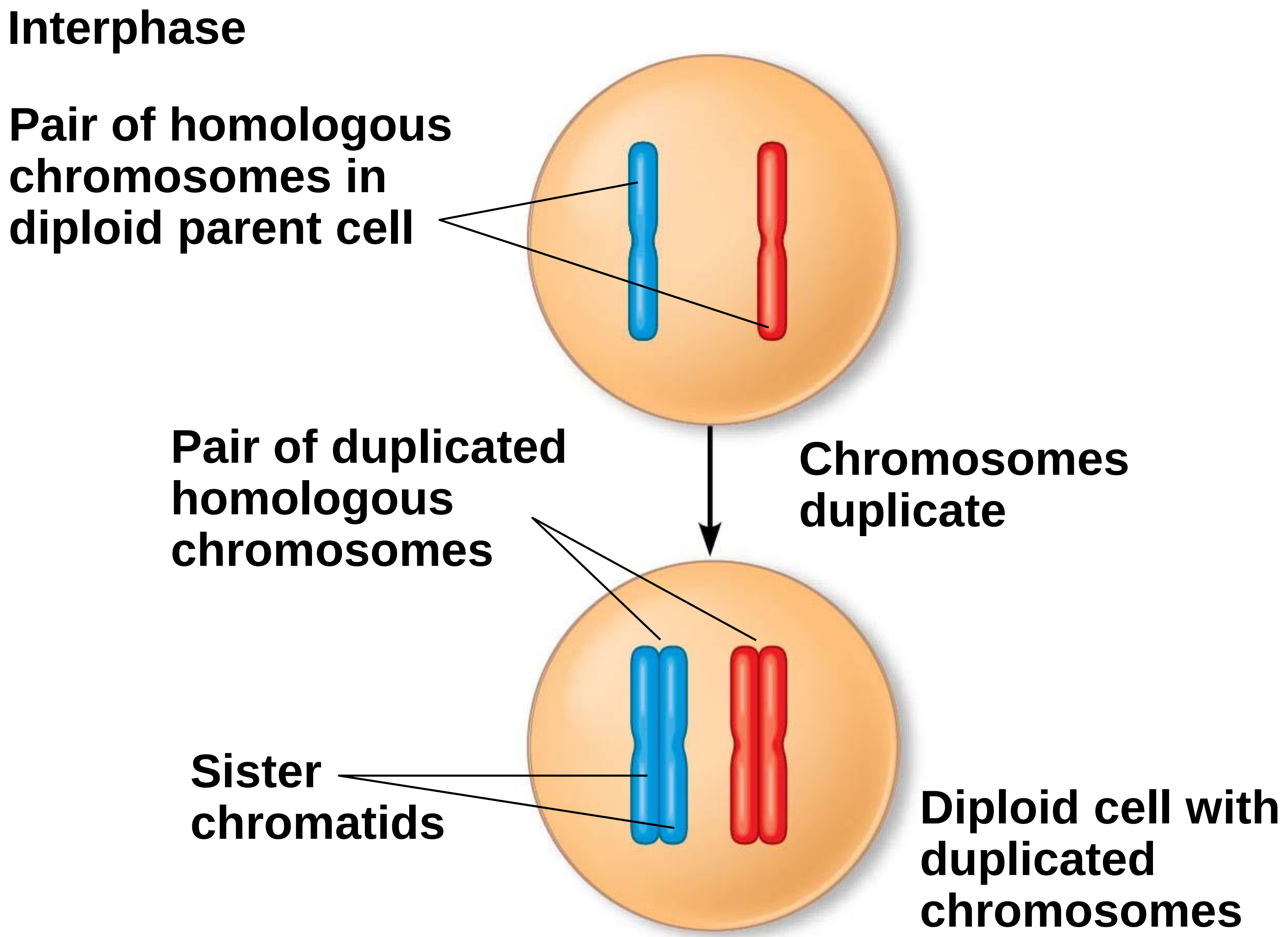
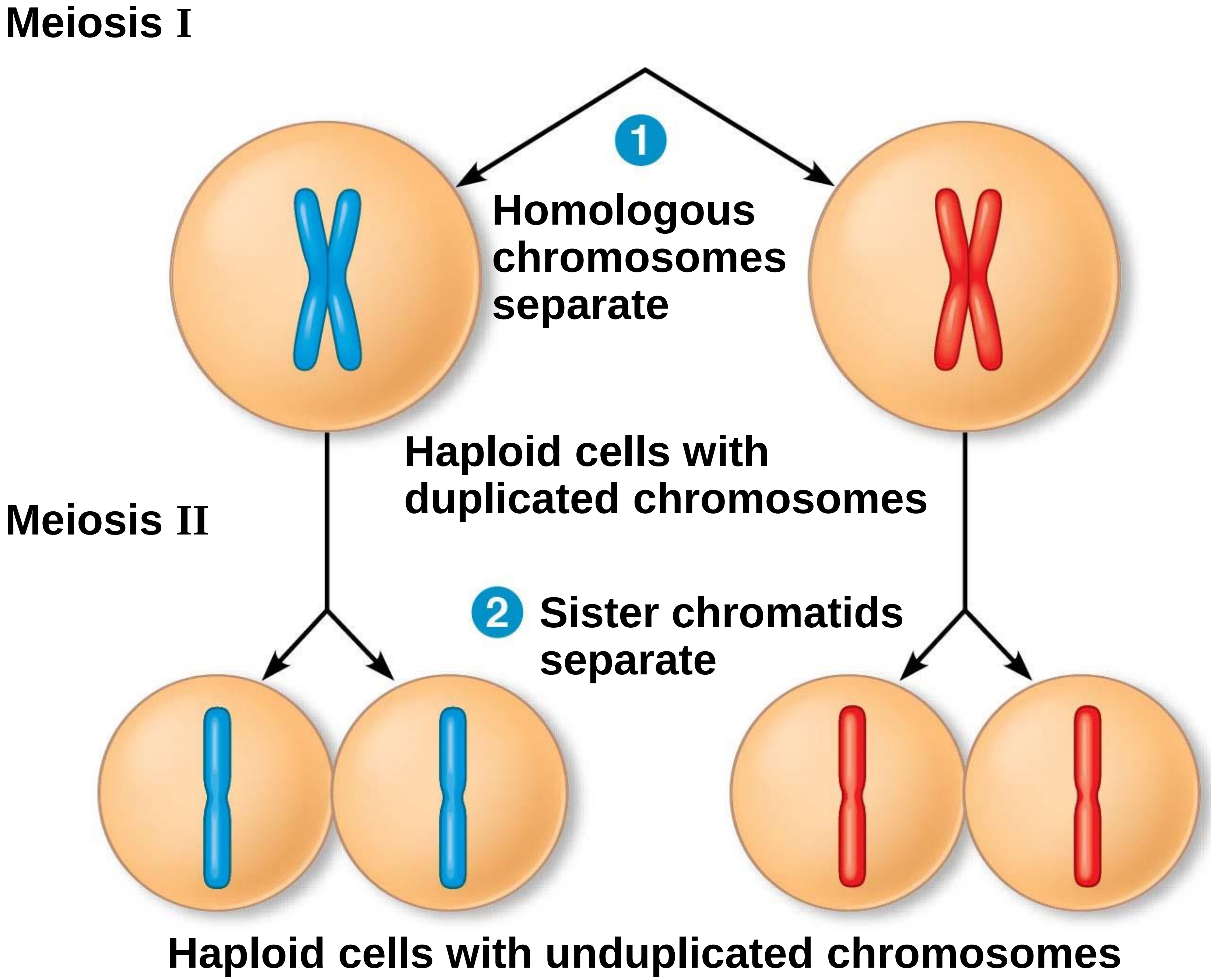

Interphase
Pair of homologous chromosomes in diploid parent cell
Pair of duplicated homologous chromosomes
Chromosomes duplicate
Sister chromatids
Diploid cell with duplicated chromosomes

Figure 10.7-2


Meiosis I
1
Homologous chromosomes separate
Haploid cells with duplicated chromosomes
Meiosis II
2
Sister chromatids separate
Haploid cells with unduplicated chromosomes

- Meiosis halves the total number of chromosomes very specifically
- It reduces the number of sets from two to one, with each daughter cell receiving one set of chromosomes

- In the first meiotic division, homologous pairs of chromosomes pair and separate
- In the second meiotic division, sister chromatids of each chromosome separate
- Four new haploid cells are produced as a result

Figure 10.8

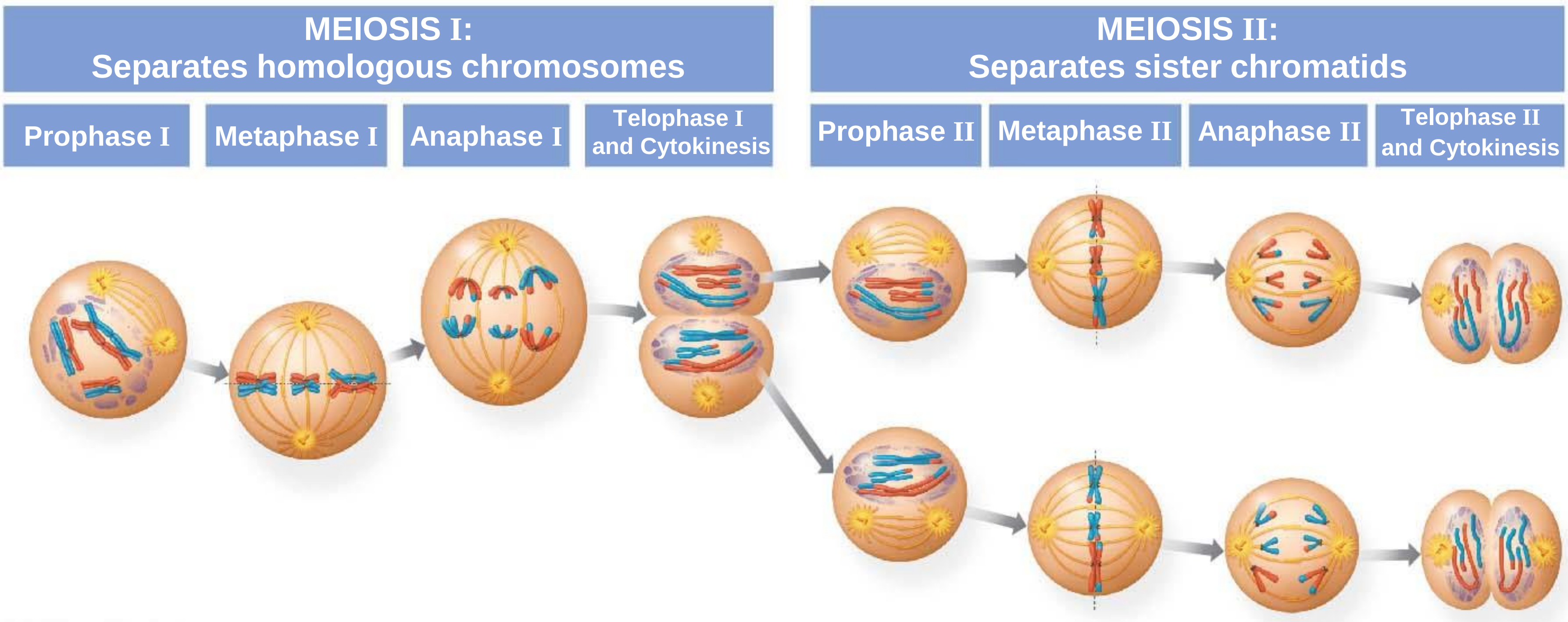
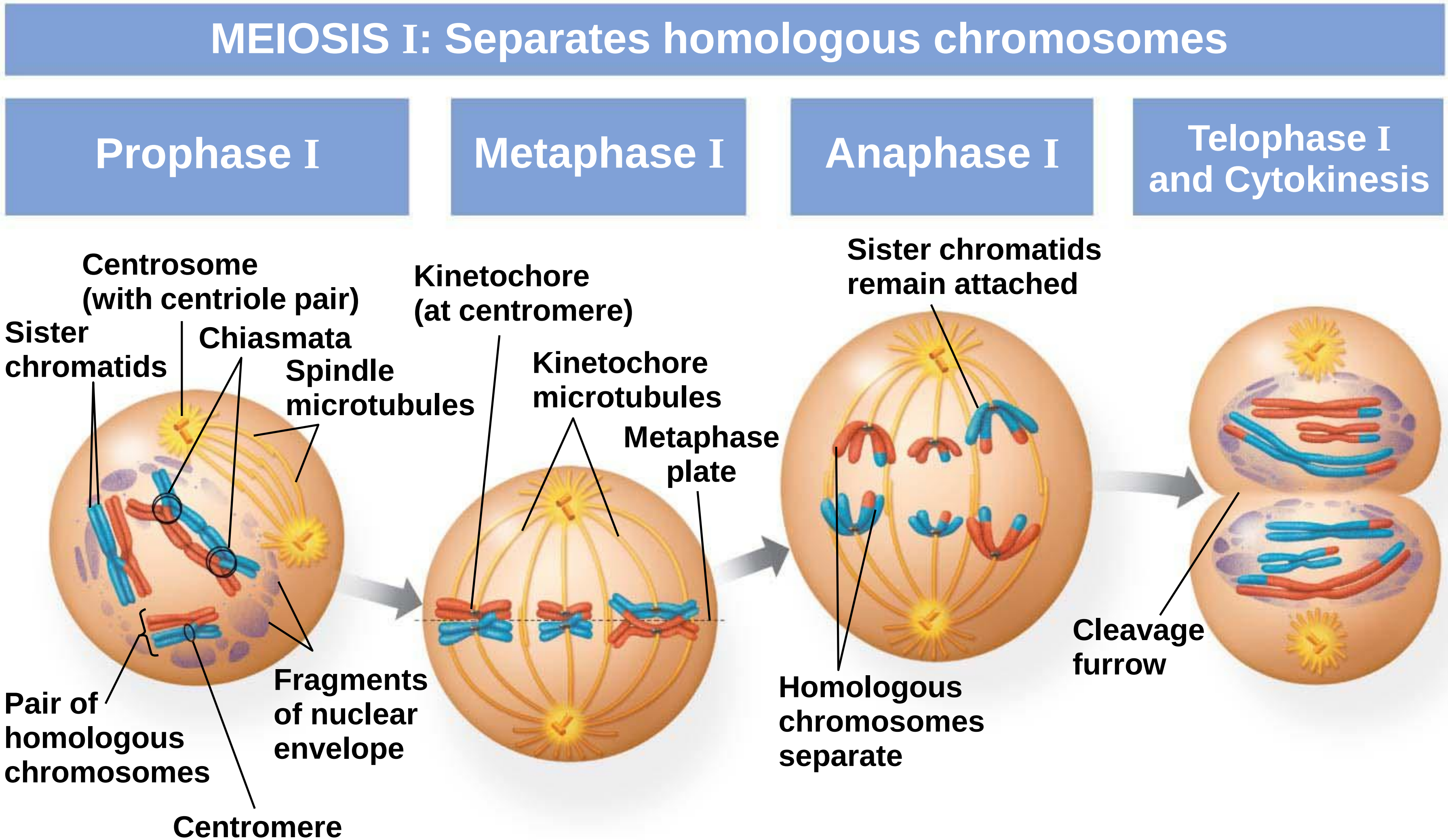

MEIOSIS I:
Separates homologous chromosomes
MEIOSIS II:
Separates sister chromatids
Prophase I
Metaphase I
Anaphase I
Telophase I and Cytokinesis
Prophase II
Metaphase II
Anaphase II
Telophase II and Cytokinesis

Figure 10.8-1



MEIOSIS I: Separates homologous chromosomes
Prophase I
Metaphase I
Anaphase I
Telophase I and Cytokinesis
Centrosome (with centriole pair)
Sister chromatids
Chiasmata
Spindle microtubules
Pair of homologous chromosomes
Fragments of nuclear envelope
Centromere
Kinetochore (at centromere)
Kinetochore microtubules
Metaphase plate
Sister chromatids remain attached
Homologous chromosomes separate
Cleavage furrow

Figure 10.8-1a

MEIOSIS I: Separates homologous chromosomes

Prophase I

Metaphase I

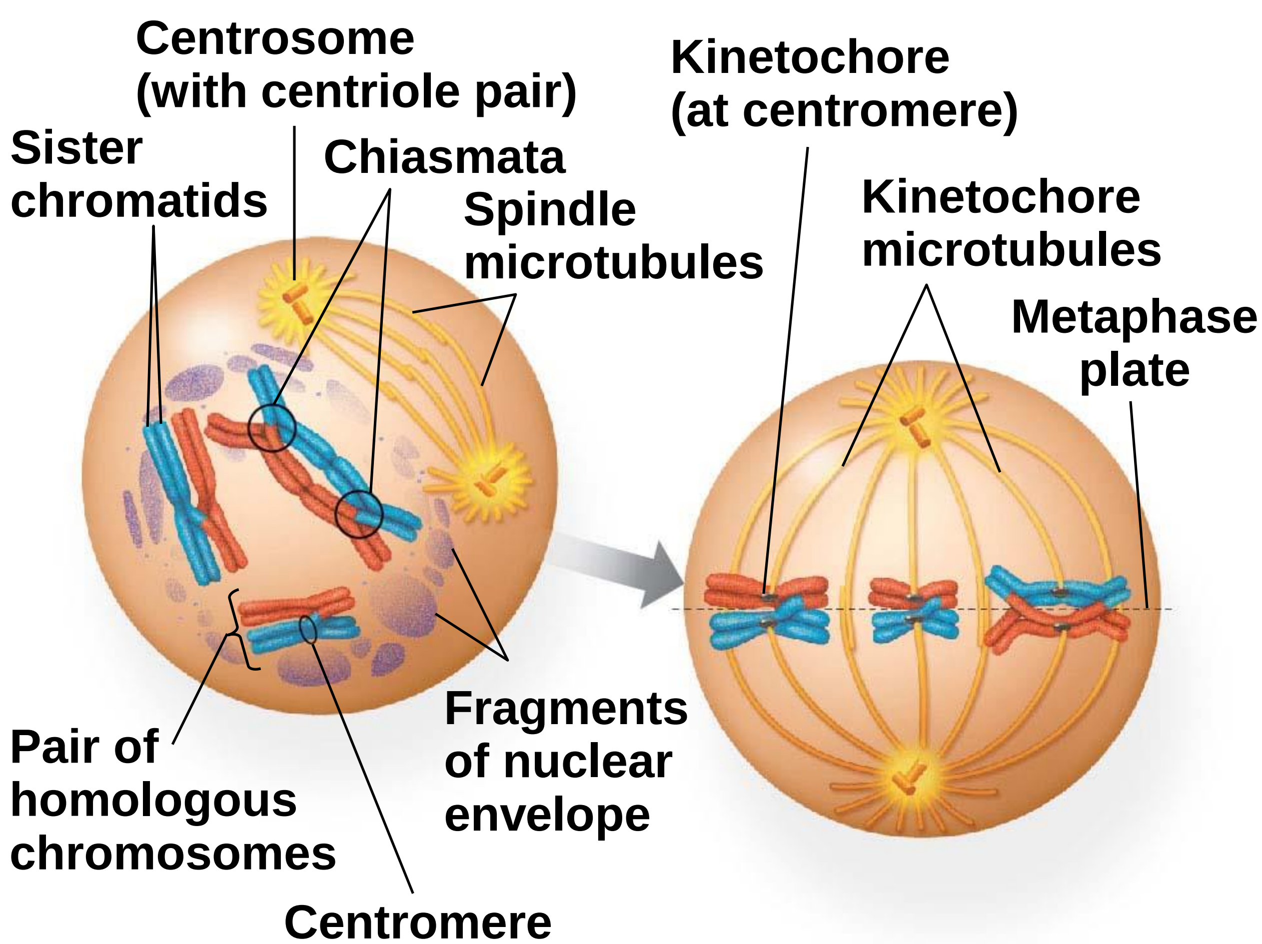


Figure 10.8-1b

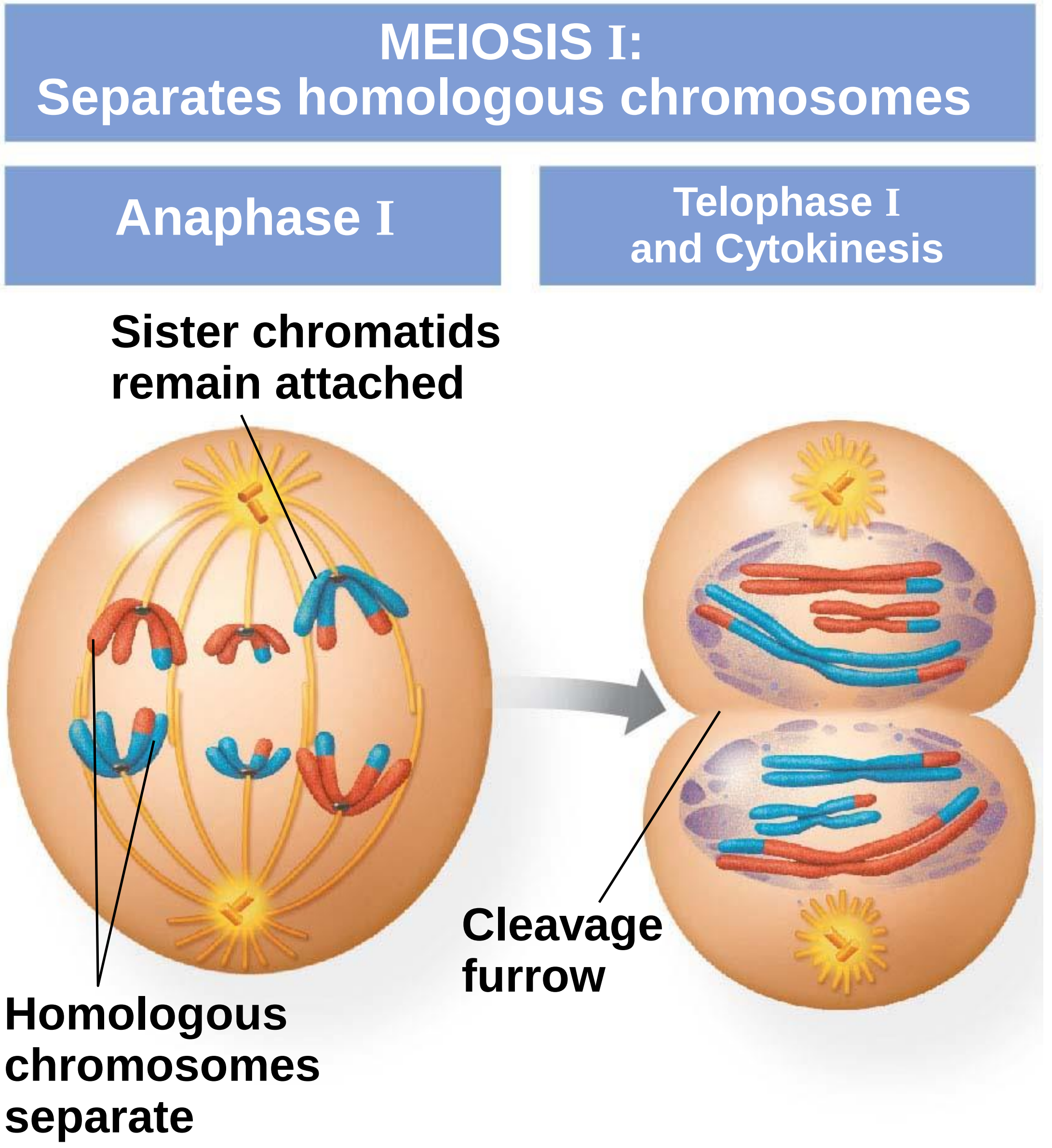
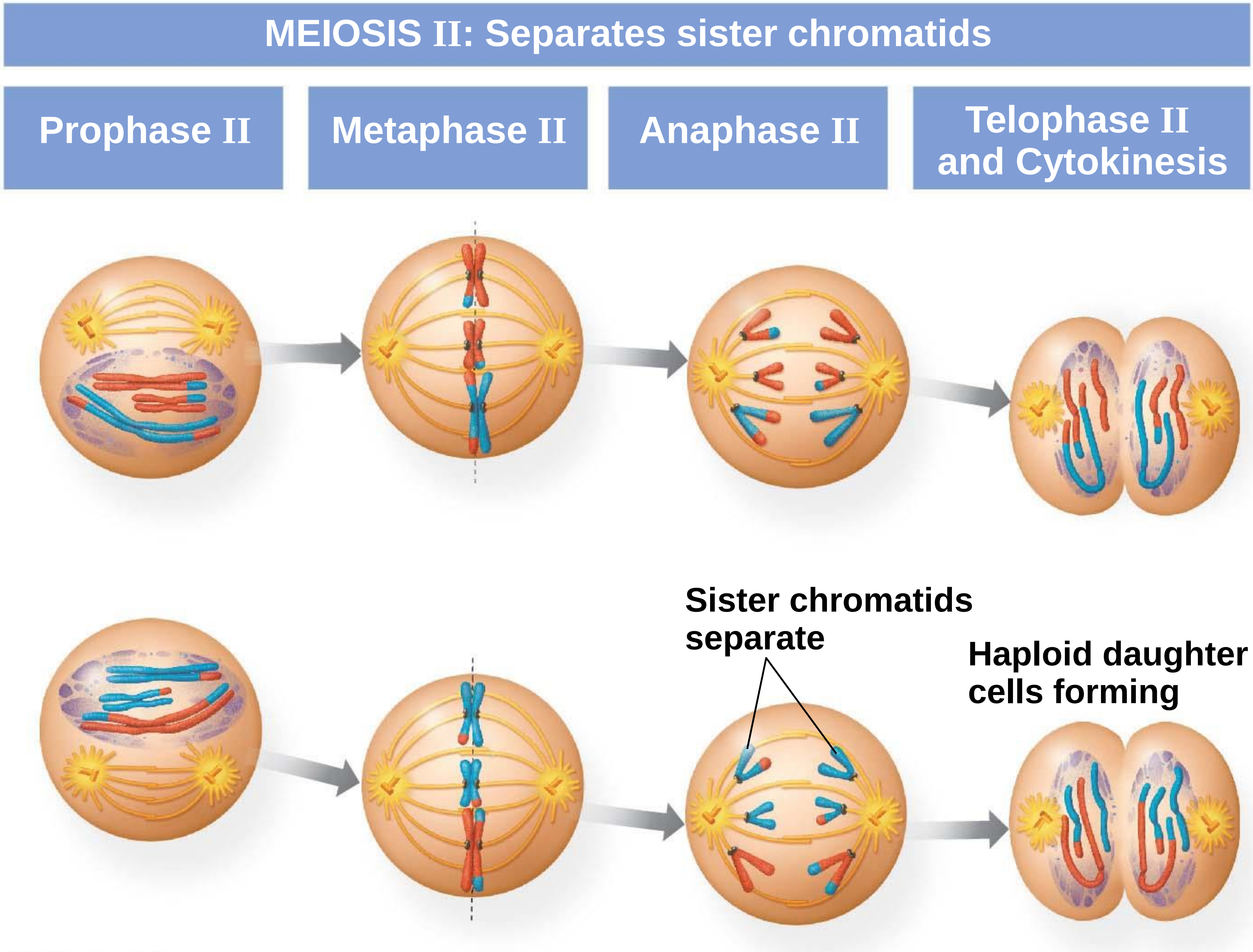


Figure 10.8-2


MEIOSIS II: Separates sister chromatids
Prophase II
Metaphase II
Anaphase II
Telophase II and Cytokinesis
Sister chromatids separate
Haploid daughter cells forming

Prophase I

- Chromosomes condense progressively throughout prophase I
- Homologous chromosomes pair up, aligned gene by gene

- In **crossing over**, nonsister chromatids exchange DNA segments
- Each homologous pair has one or more X-shaped regions called **chiasmata**
- Chiasmata exist at points where crossing over has occurred.

Metaphase I

- In metaphase I, homologous pairs line up at the metaphase plate, with one chromosome facing each pole
- Microtubules from one pole are attached to the kinetochore of one chromosome of each tetrad
- Microtubules from the other pole are attached to the kinetochore of the other chromosome

Anaphase I

- In anaphase I, pairs of homologous chromosomes separate
- One chromosome moves toward each pole, guided by the spindle apparatus
- Sister chromatids remain attached at the centromere and move as one unit toward the pole

Telophase I and Cytokinesis

- In the beginning of telophase I, each half of the cell has a haploid set of chromosomes
- Each chromosome still consists of two sister chromatids
- Cytokinesis usually occurs simultaneously, forming two haploid daughter cells

- In animal cells, a cleavage furrow forms; in plant cells, a cell plate forms
- No chromosome duplication occurs between the end of meiosis I and the beginning of meiosis II because the chromosomes are already replicated

- Division in meiosis II also occurs in four phases
  - Prophase II
  - Metaphase II
  - Anaphase II
  - Telophase II and cytokinesis
- Meiosis II is very similar to mitosis

Prophase II

- In prophase II, a spindle apparatus forms
- In late prophase II, chromosomes (each still composed of two chromatids) move toward the metaphase plate

Metaphase II

- The sister chromatids are arranged at the metaphase plate
- Because of crossing over in meiosis I, the two sister chromatids of each chromosome are no longer genetically identical
- The kinetochores of sister chromatids attach to microtubules extending from opposite poles

Anaphase II

- In anaphase II, the sister chromatids separate
- The sister chromatids of each chromosome now move as two newly individual chromosomes toward opposite poles

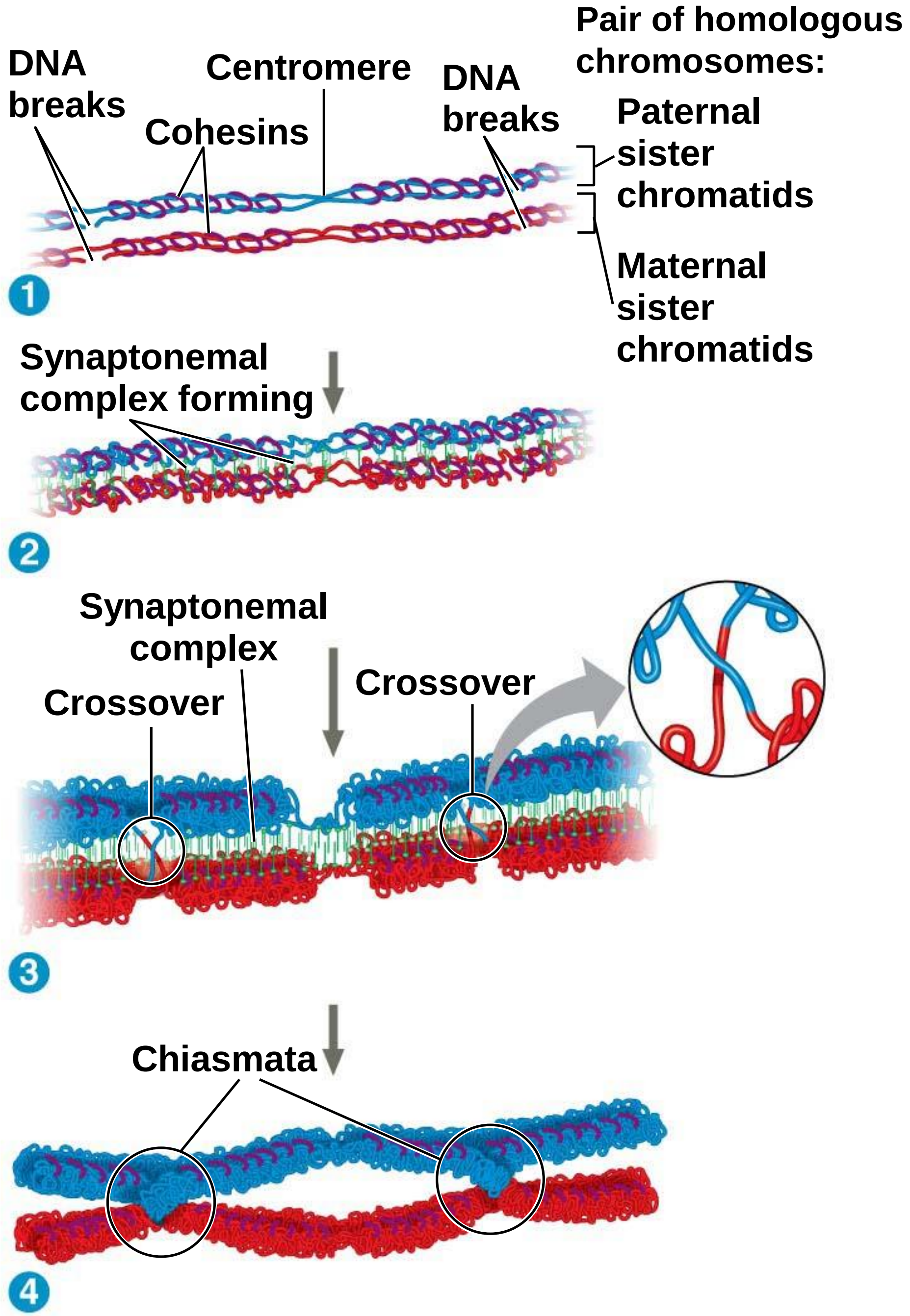
Telophase II and Cytokinesis

- Nuclei form, and the chromosomes begin decondensing
- At the end of meiosis, there are four daughter cells, each with a haploid set of unduplicated chromosomes
- Each daughter cell is genetically distinct from the others and from the parent cell

Crossing Over and Synapsis During Prophase I

- During prophase I, two members of a homologous pair associate along their length, allele by allele
- A zipper-like structure called the **synaptonemal complex** forms during this attachment (**synapsis**)
- DNA molecules of the maternal and paternal chromatid are broken at matching points
- The DNA breaks are closed so that a paternal chromatid is joined to a piece of maternal chromatid, and vice versa

Figure 10.9



DNA breaks
Centromere
Cohesins
DNA breaks
Pair of homologous chromosomes:
Paternal sister chromatids
Maternal sister chromatids
1
Synaptonemal complex forming
2
Synaptonemal complex
Crossover
Crossover
3
Chiasmata
4

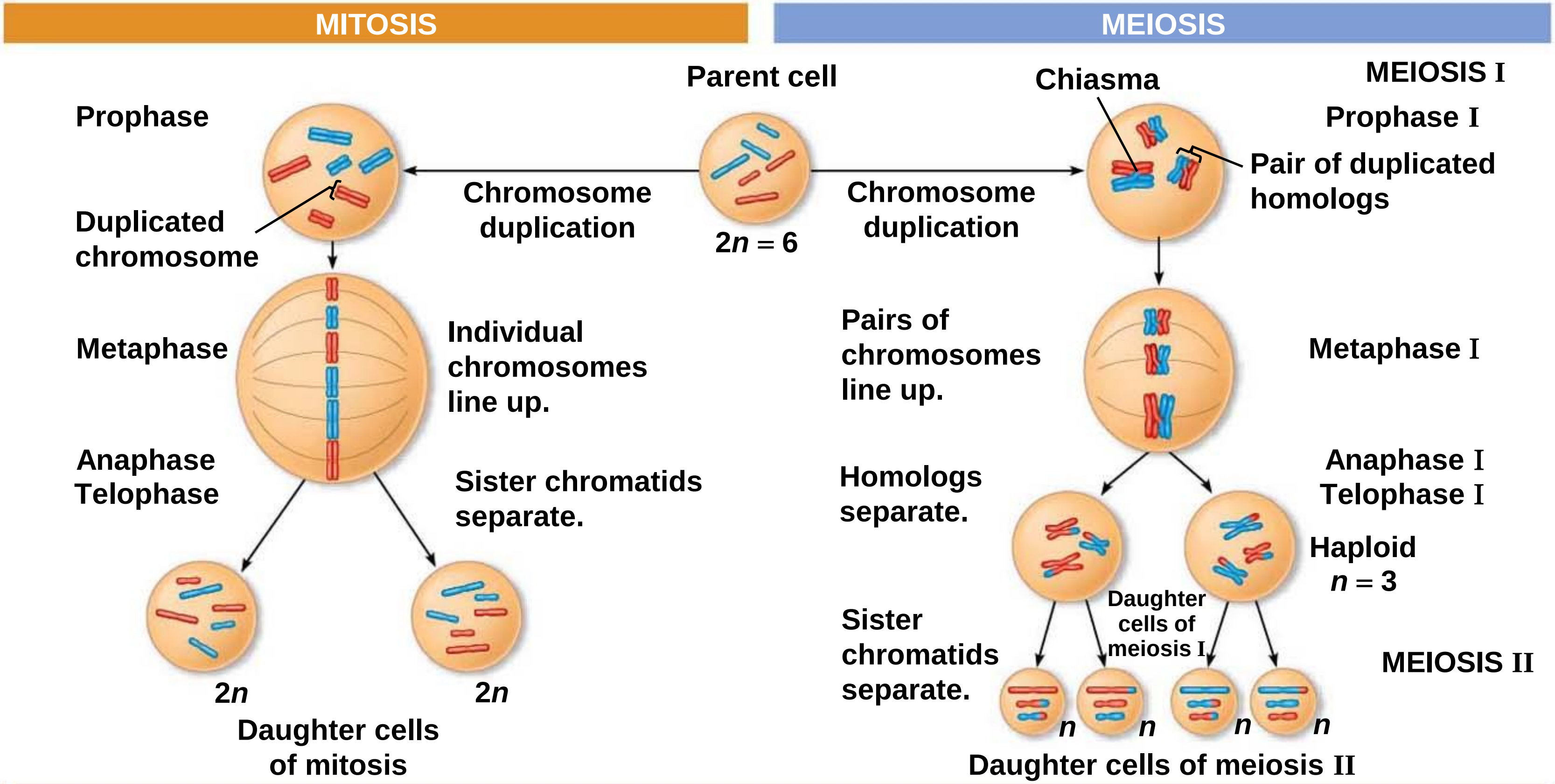
A Comparison of Mitosis and Meiosis

- Mitosis conserves the number of chromosome sets, producing cells that are genetically identical to the parent cell
- Meiosis reduces the number of chromosome sets from two (diploid) to one (haploid), producing cells that differ genetically from each other and from the parent cell
- Meiosis includes two divisions after replication, each with specific stages

- Three events are unique to meiosis, and all three occur in meiosis I
  - **Synapsis and crossing over** in prophase I: Homologous chromosomes physically connect and exchange genetic information
  - **Alignment of homologous pairs at the metaphase plate**: Homologous pairs of chromosomes are positioned there in metaphase I
  - **Separation of homologs** during anaphase I

- Sister chromatids stay together due to sister chromatid cohesion
- In mitosis, cohesins are cleaved at the end of metaphase
- In meiosis, cohesins are cleaved along the chromosome arms in anaphase I (separation of homologs) and at the centromeres in anaphase II (separation of sister chromatids)

Figure 10.10



SUMMARY

Property	Mitosis (diploid and haploid)	Meiosis (diploid only)
DNA replication	Occurs during interphase before mitosis begins	Occurs during interphase before meiosis I begins
Number of divisions	One, including prophase, prometaphase, metaphase, anaphase, and telophase	Two, each including prophase, metaphase, anaphase, and telophase
Synapsis of homologous chromosomes	Does not occur	Occurs during prophase I along with crossing over between nonsister chromatids; resulting chiasmata hold pairs together due to sister chromatid cohesion
Number of daughter cells and genetic composition	Two, each genetically identical to the parent cell, with the same number of chromosomes	Four, each haploid (*n*); genetically different from the parent cell and from each other
Role in the animal or plant body	Enables multicellular animal or plant (gametophyte or sporophyte) to arise from a single cell; produces cells for growth, repair, and, in some species, asexual reproduction; produces gametes in the gametophyte plant	Produces gametes (in animals) or spores (in the sporophyte plant); reduces number of chromosome sets by half and introduces genetic variability among the gametes or spores

Figure 10.10-2

Concept 10.4: Genetic variation produced in sexual life cycles contributes to evolution

- Mutations (changes in an organism's DNA) are the original source of genetic diversity
- Mutations create different versions of genes called alleles
- Reshuffling of alleles during sexual reproduction produces genetic variation

Origins of Genetic Variation Among Offspring

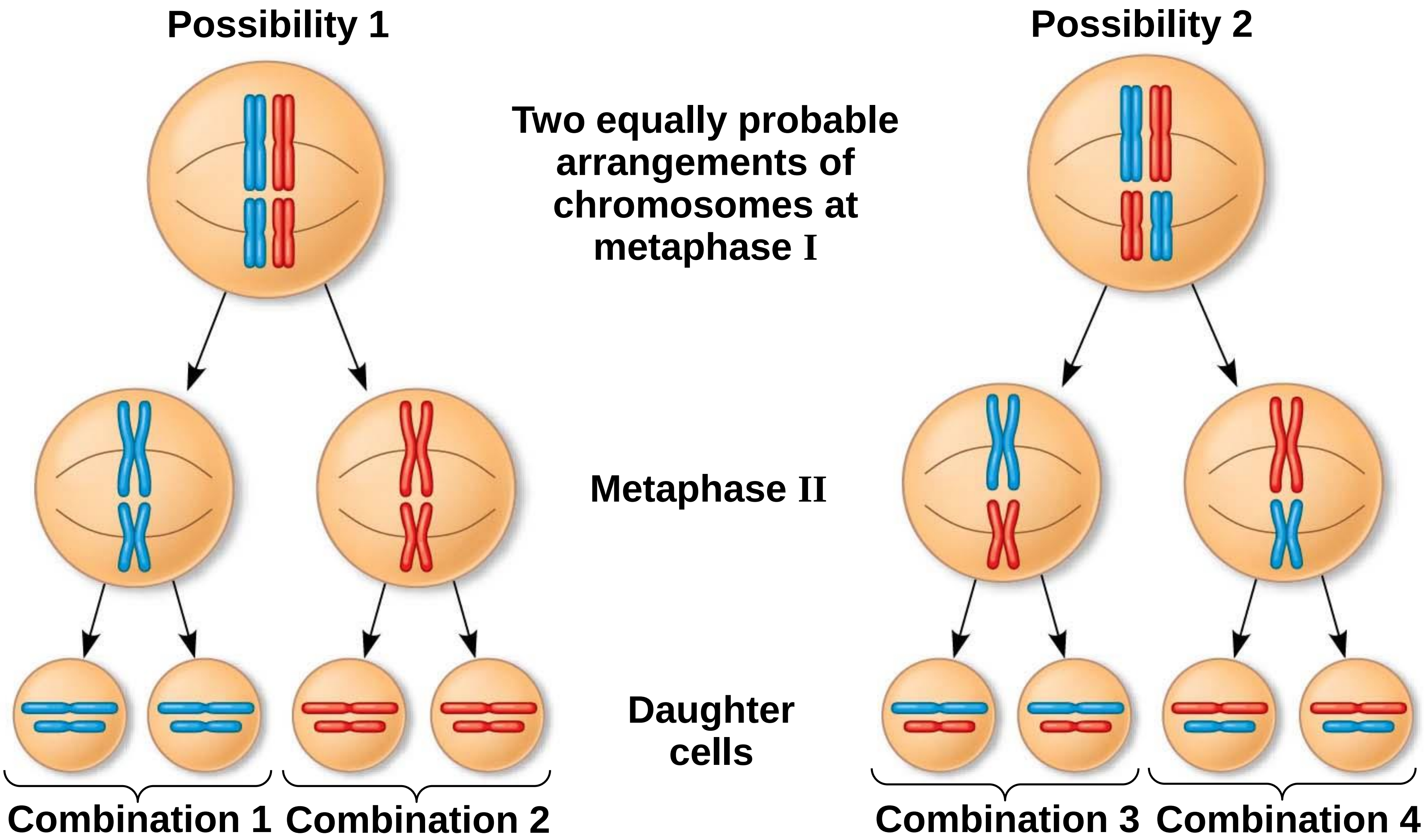
- The behavior of chromosomes during meiosis and fertilization is responsible for most of the variation that arises in each generation
- Three mechanisms contribute to genetic variation
  - Independent assortment of chromosomes
  - Crossing over
  - Random fertilization

Independent Assortment of Chromosomes

- Homologous pairs of chromosomes orient randomly at metaphase I of meiosis
- In independent assortment, each pair of chromosomes sorts maternal and paternal homologs into daughter cells independently of the other pairs

- The number of combinations possible when chromosomes assort independently into gametes is 2^n, where n is the haploid number
- For humans ($n = 23$), there are more than 8 million (2^{23}) possible combinations of chromosomes

Figure 10.11-s3

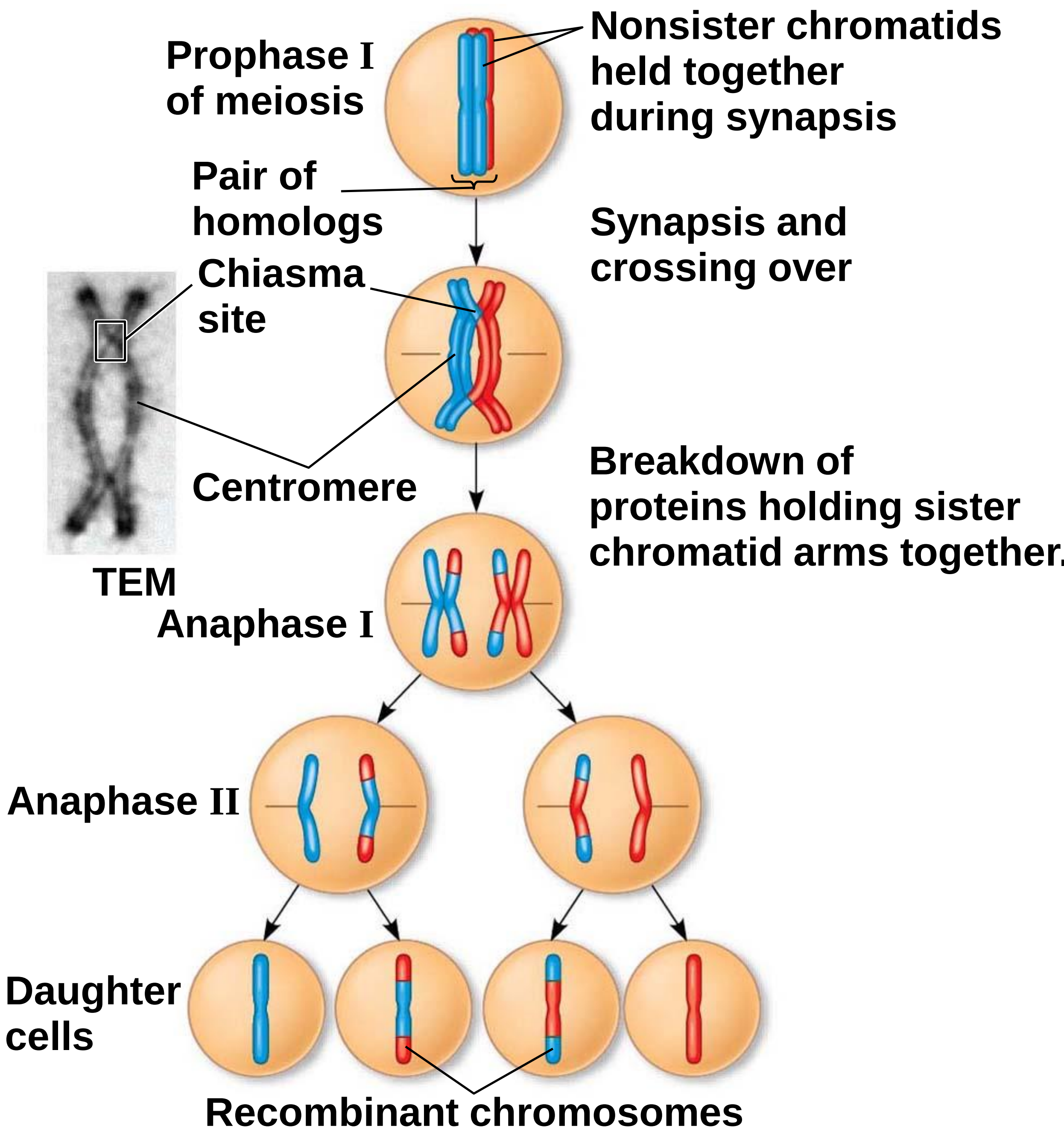


Crossing Over

- Crossing over produces **recombinant chromosomes**, which combine DNA inherited from each parent
- In meiosis in humans, on average, one to three crossover events occur per chromosome pair

- Crossing over contributes to genetic variation by combining DNA, producing chromosomes with new combinations of maternal and paternal alleles

Figure 10.12-s5



Random Fertilization

- Random fertilization adds to genetic variation because any sperm can fuse with any ovum (unfertilized egg)
- The fusion of two gametes (each with 8.4 million possible chromosome combinations from independent assortment) produces a zygote with any of about 70 trillion diploid combinations

- Crossing over adds even more variation
- Each zygote has a unique genetic identity

The Evolutionary Significance of Genetic Variation Within Populations

- Natural selection results in the accumulation of genetic variations favored by the environment
- Sexual reproduction contributes to the genetic variation in a population, which originates from mutations

- Asexual reproduction is less expensive than sexual reproduction
- Nonetheless, sexual reproduction is nearly universal among animals
- Overall, genetic variation is evolutionarily advantageous

Figure 10.6

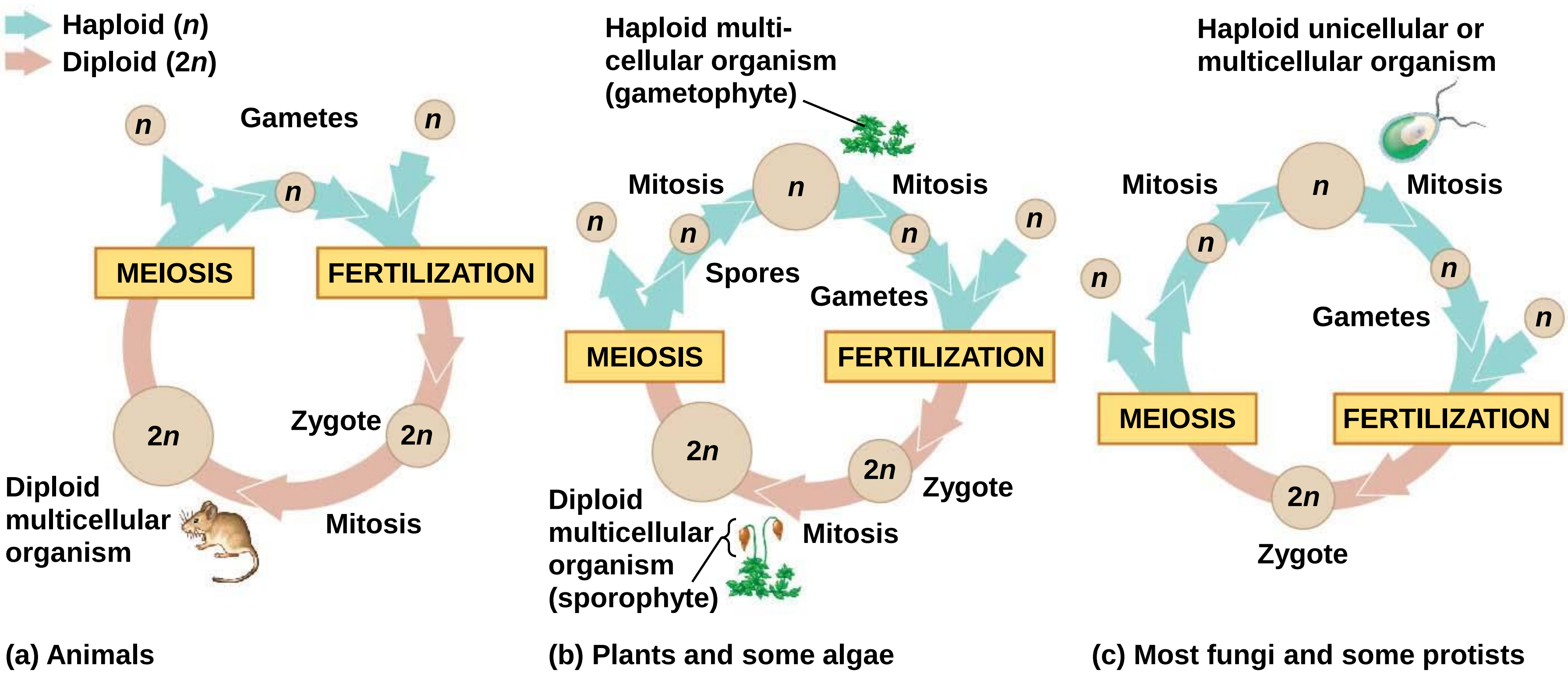
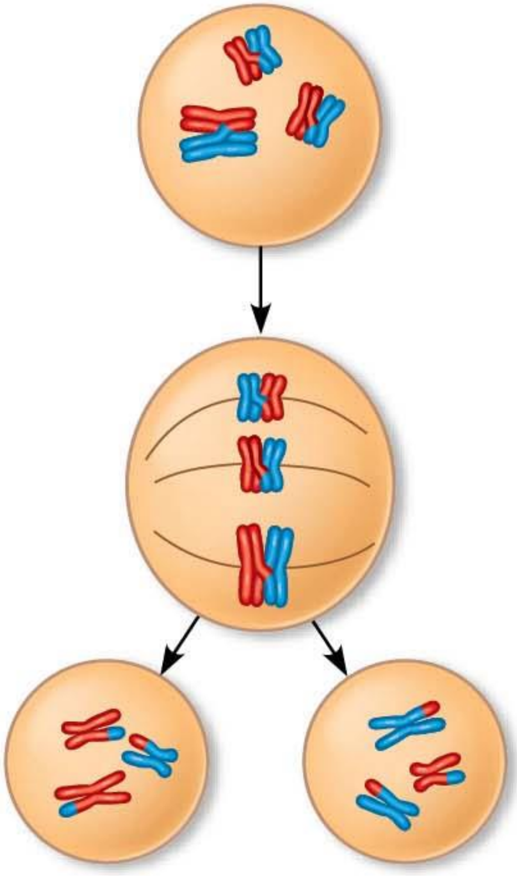

Haploid (n)
Diploid (2n)
Gametes
n
MEIOSIS
FERTILIZATION
2n
Zygote
Diploid multicellular organism
Mitosis
(a) Animals
Haploid multi-cellular organism (gametophyte)
Mitosis
Spores
Gametes
Diploid multicellular organism (sporophyte)
(b) Plants and some algae
Haploid unicellular or multicellular organism
(c) Most fungi and some protists

Figure 10.UN01-1

Figure 10.UN02



Prophase I: Each pair of homologous chromosomes undergoes synapsis and crossing over between nonsister chromatids with the subsequent appearance of chiasmata.

Metaphase I: Chromosomes line up as homologous pairs on the metaphase plate.

Anaphase I: Homologs separate from each other; sister chromatids remain joined at the centromere.