

# Overview: Variations on a Theme

- Living organisms are distinguished by their ability to reproduce their own kind
- **Genetics** is the scientific study of heredity and variation
- **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



Figure 13.1





# **Concept 13.1: Offspring acquire genes from parents by inheriting chromosomes**

- In a literal sense, children do not inherit particular physical traits from their parents
- It is genes that are actually inherited

# 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)
- Each gene has a specific location called a **locus** on a certain chromosome
- Most DNA is packaged into chromosomes



# Comparison of Asexual and Sexual Reproduction

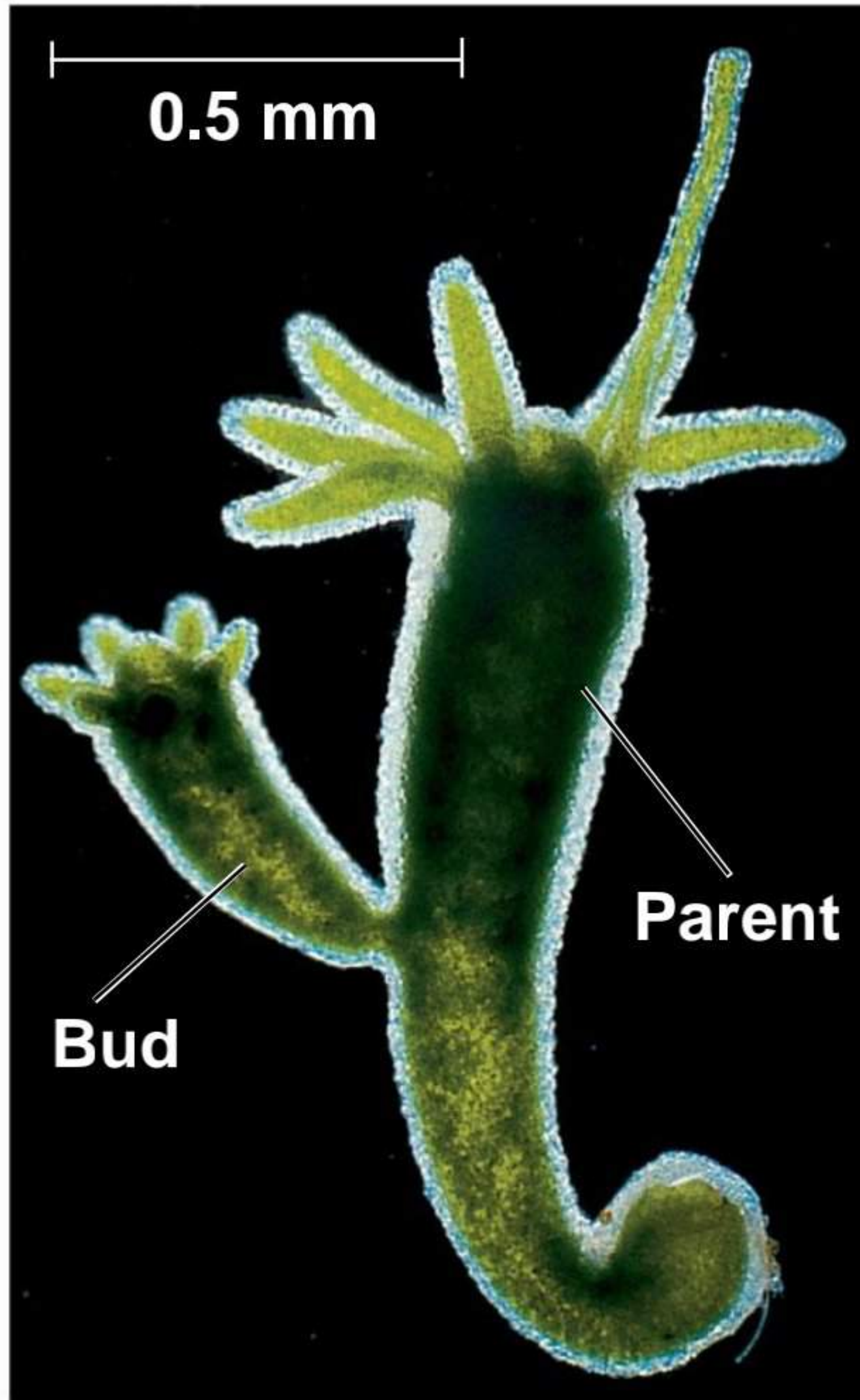
- In **asexual reproduction**, a single individual passes genes to its offspring without the fusion of gametes
- A **clone** is a group of genetically identical individuals from the same parent
- In **sexual reproduction**, two parents give rise to offspring that have unique combinations of genes inherited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



Video: Hydra Budding



Figure 13.2



**(a) Hydra**

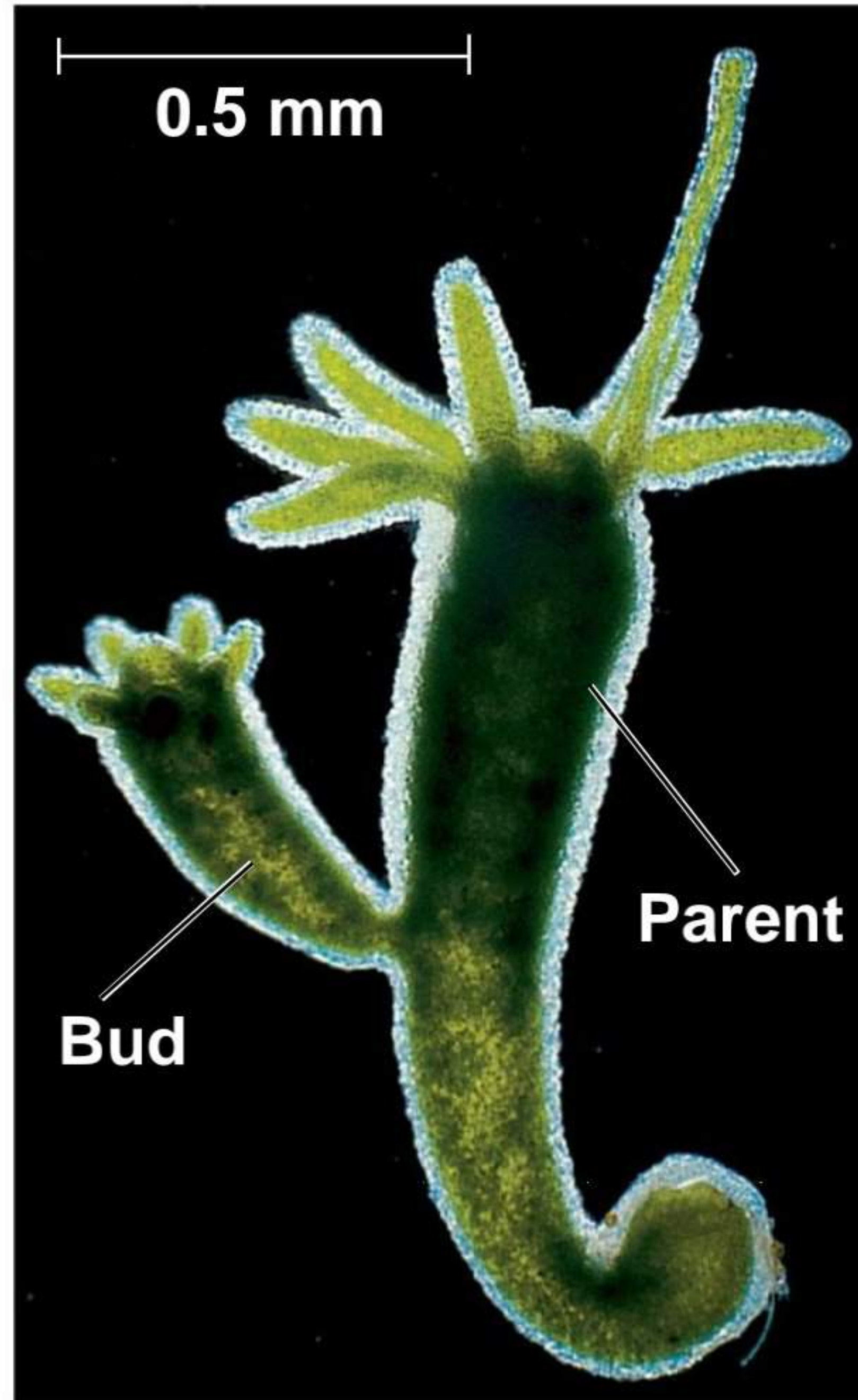
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**(b) Redwoods**



Figure 13.2a



**(a) Hydra**

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Figure 13.2b



**(b) Redwoods**

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# Concept 13.2: 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** (any cell other than a gamete) 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



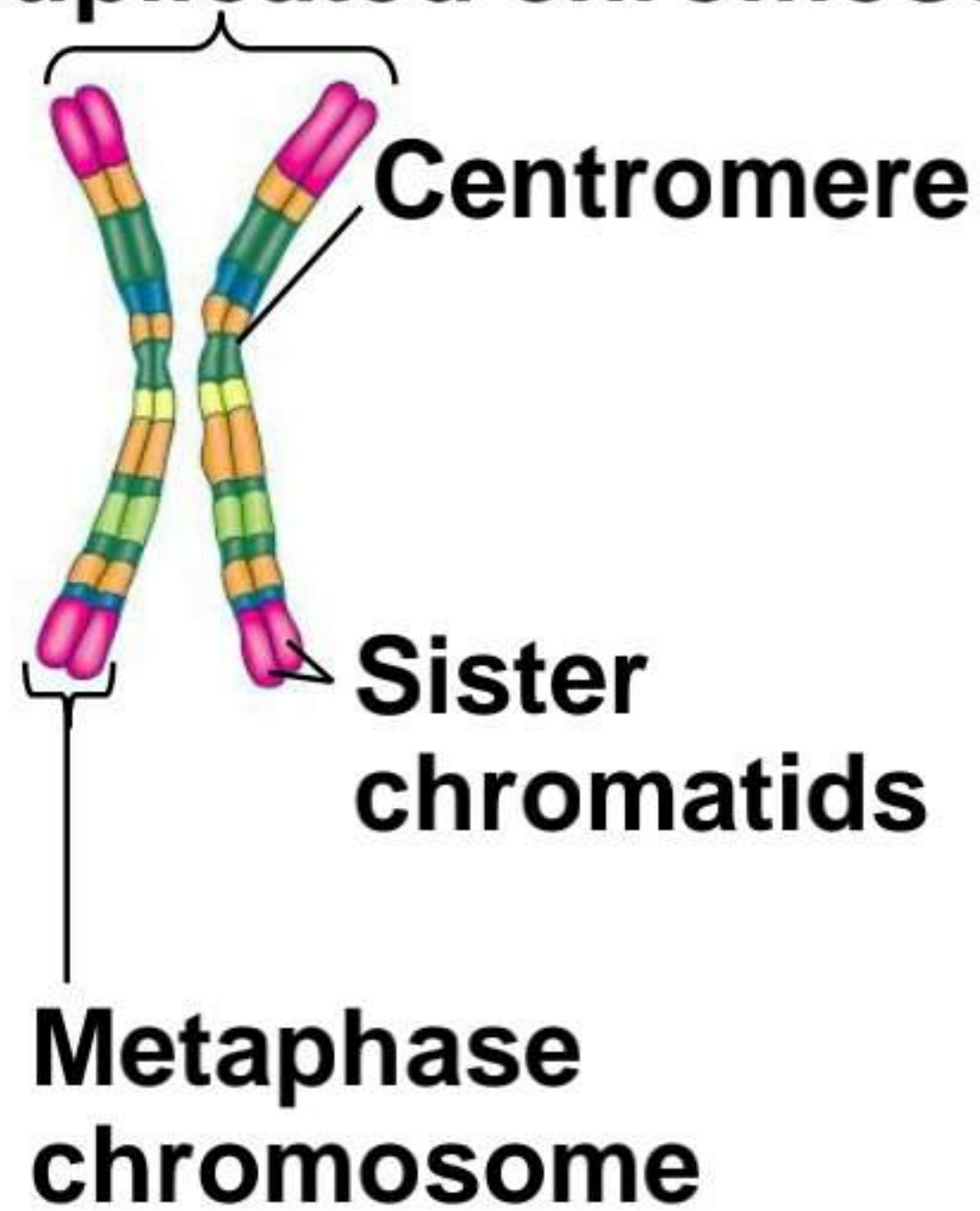
Figure 13.3

## APPLICATION



## TECHNIQUE

Pair of homologous duplicated chromosomes



5  $\mu$ m

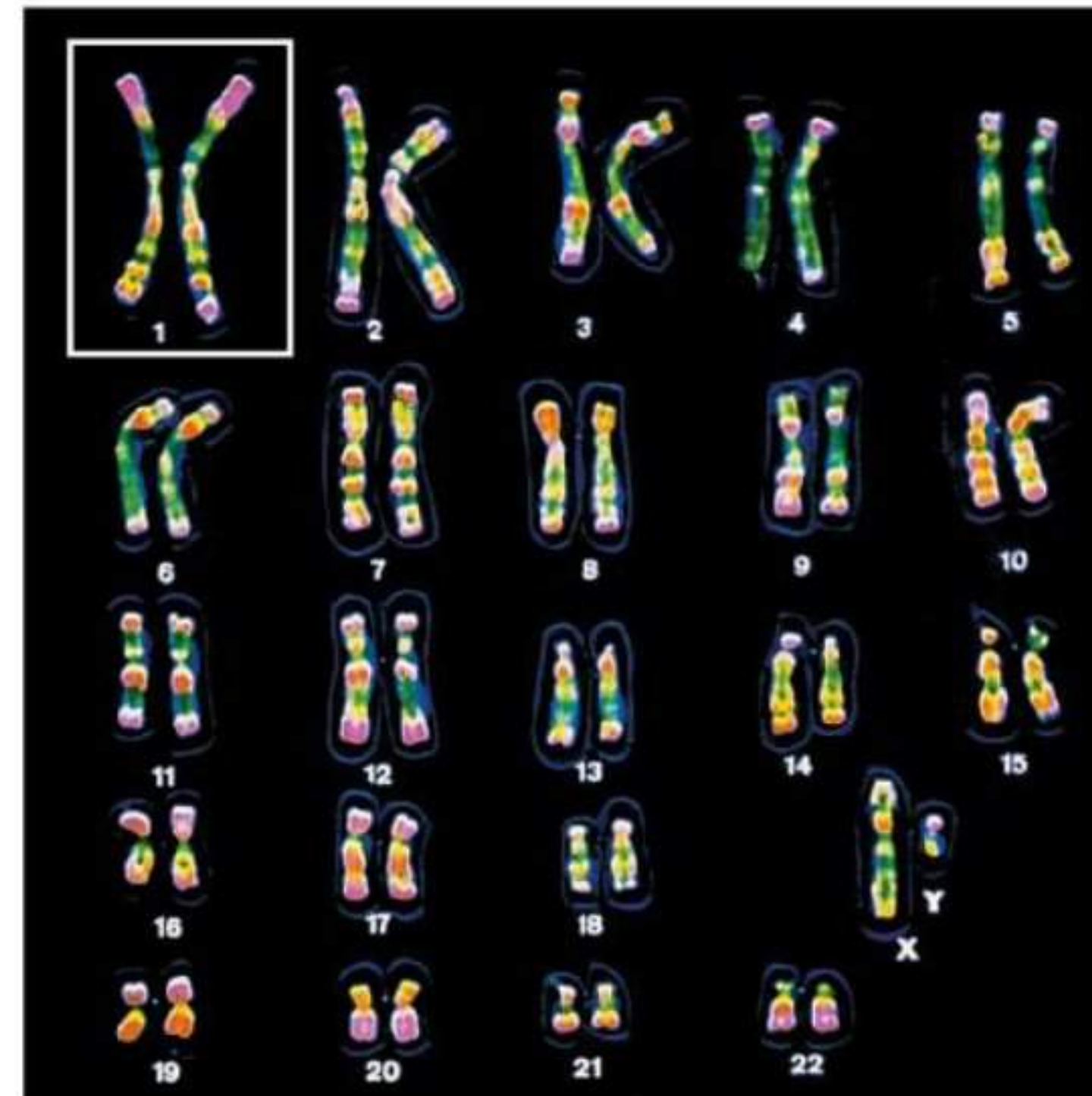




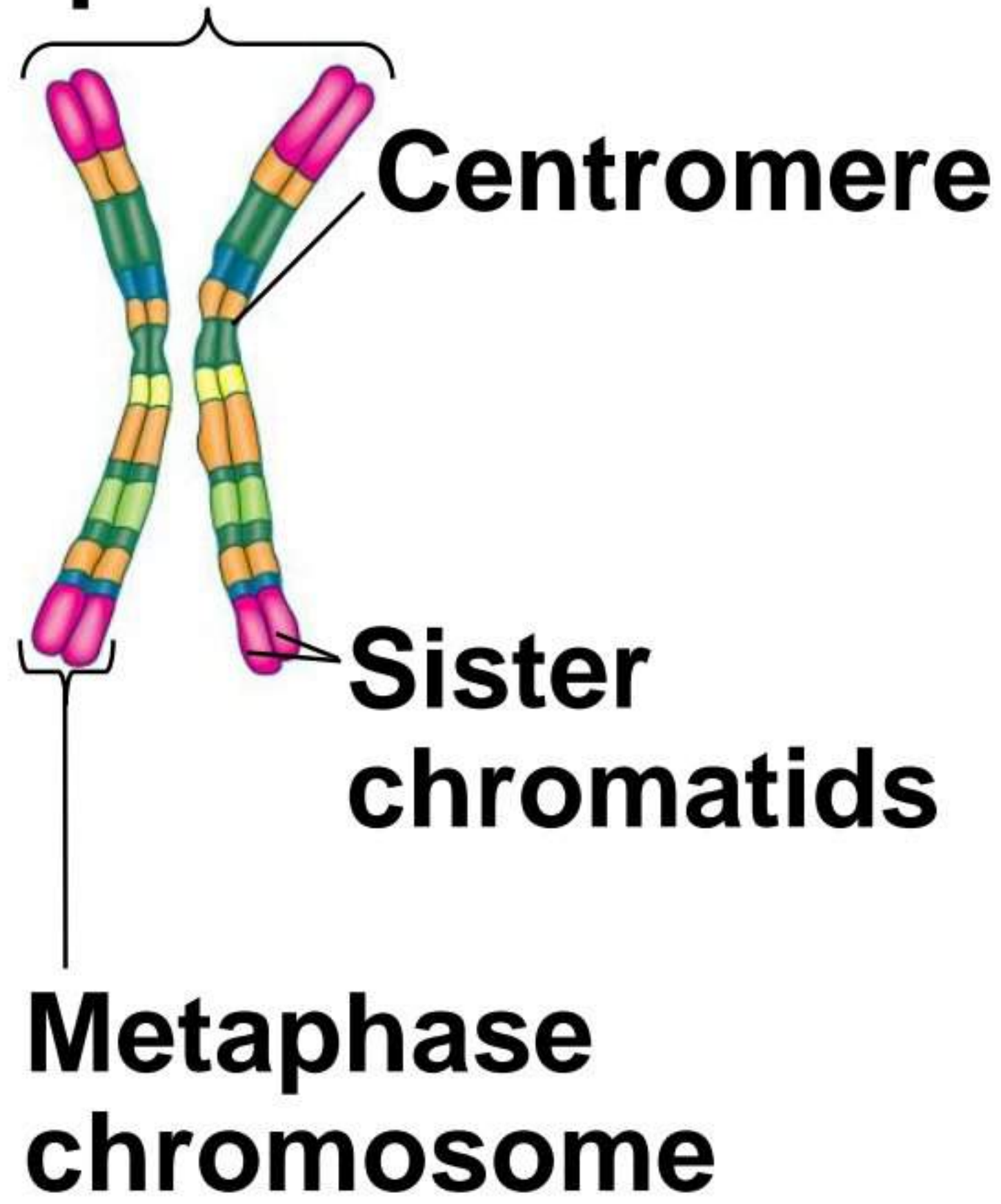
Figure 13.3a



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# Pair of homologous duplicated chromosomes



5  $\mu\text{m}$

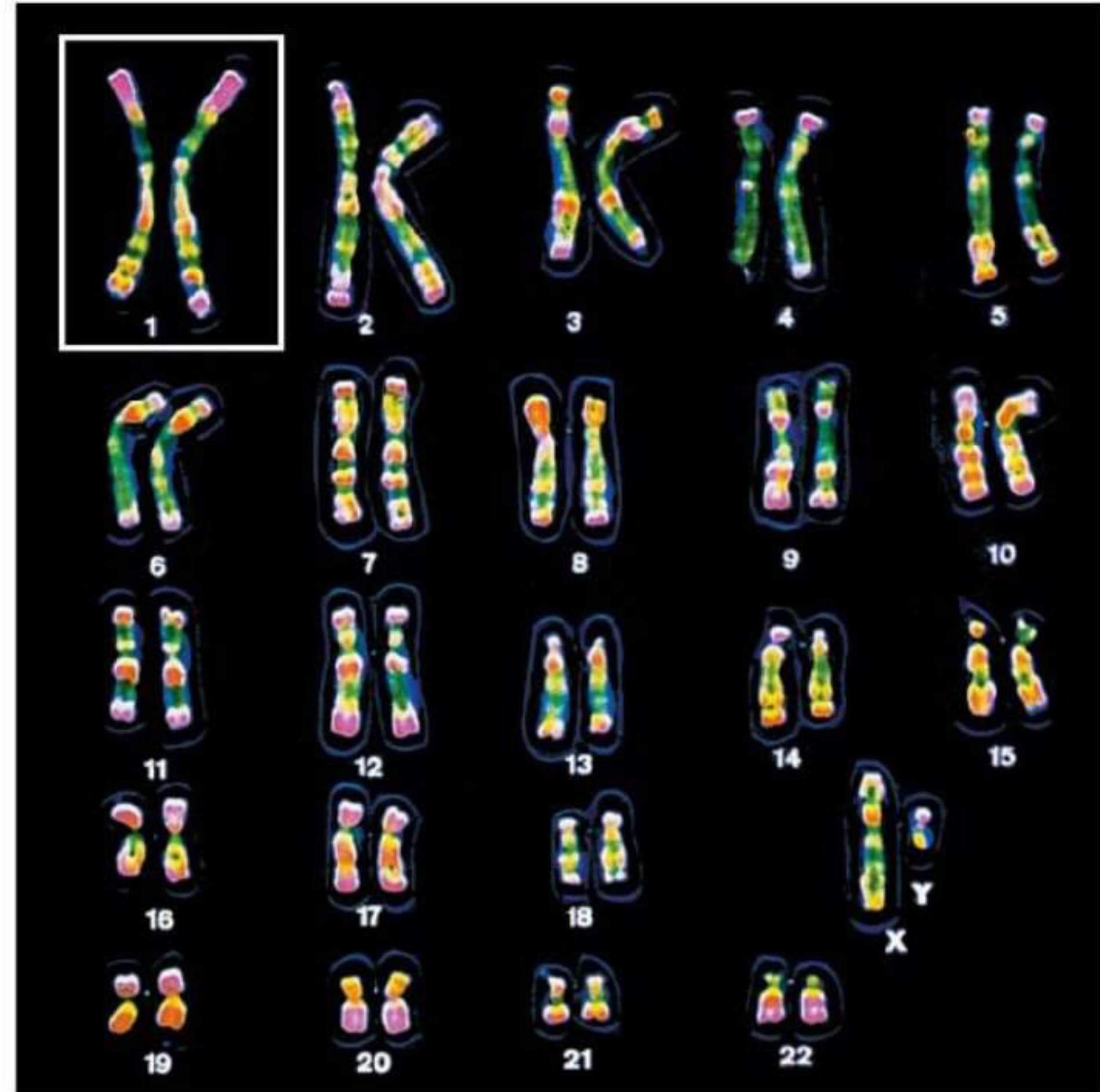
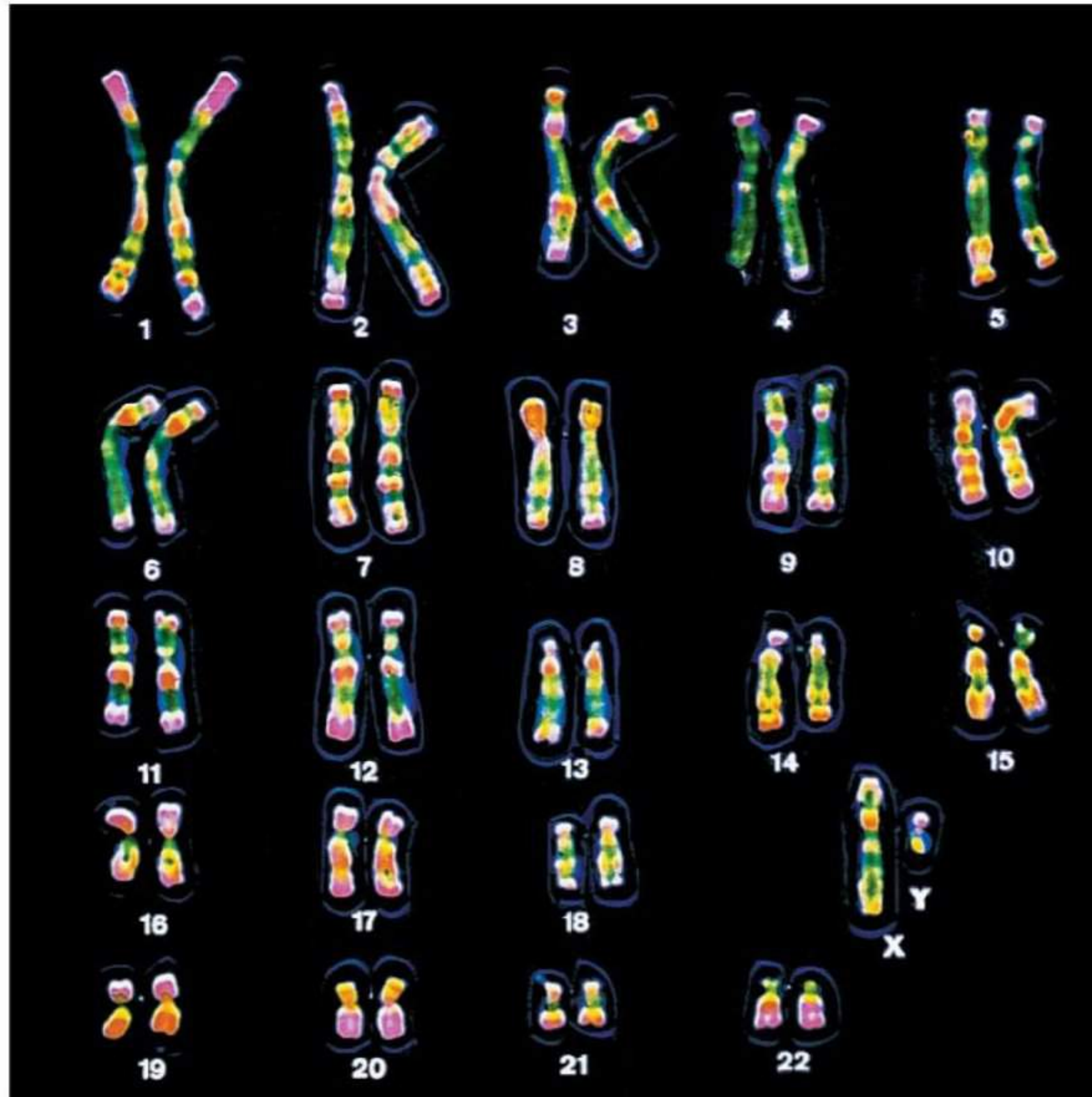




Figure 13.3c

5  $\mu\text{m}$





- 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** ( $2n$ ) 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 13.4

**Key**

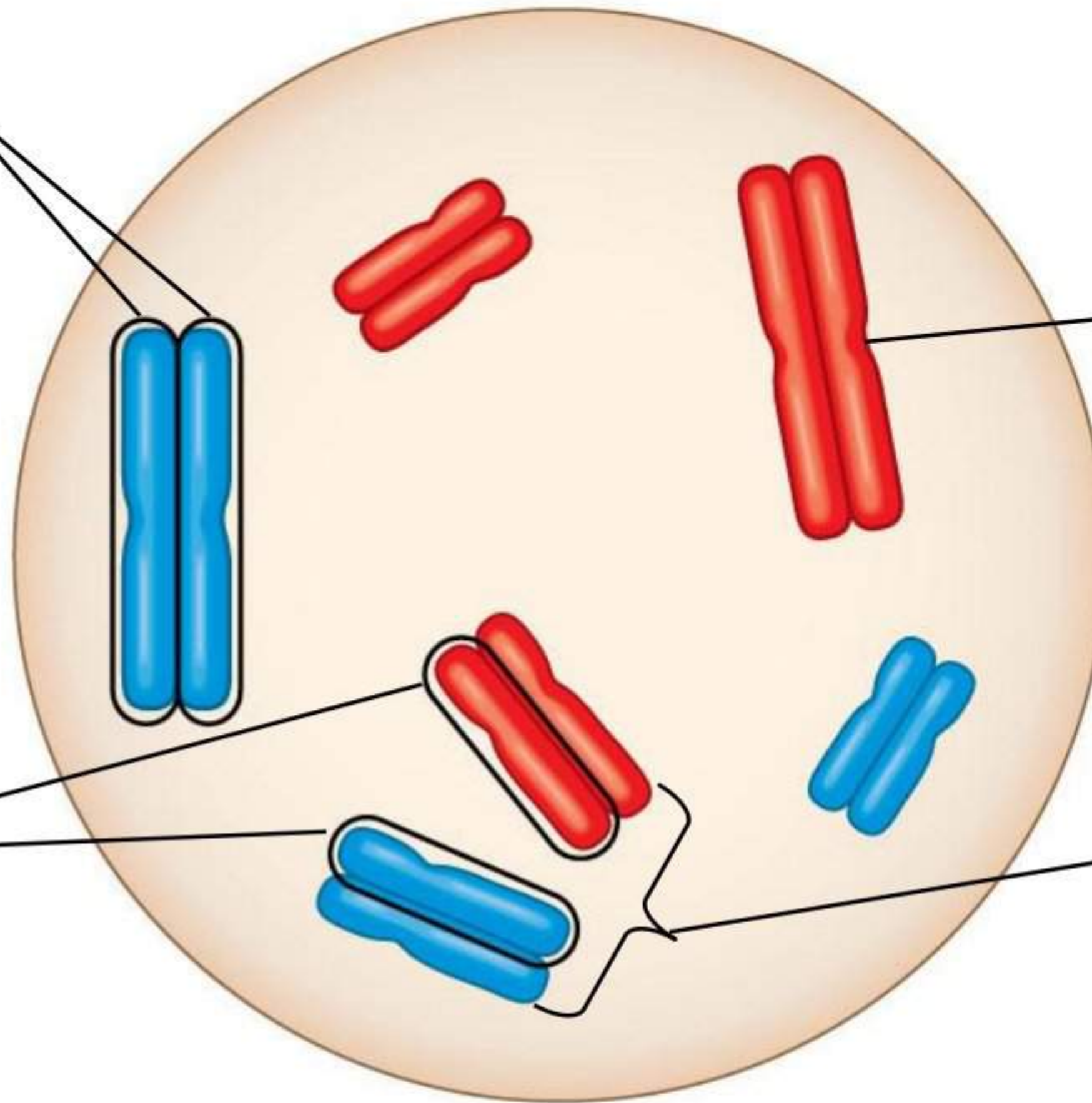
- $2n = 6$  {
- Maternal set of chromosomes ( $n = 3$ )
  - Paternal set of chromosomes ( $n = 3$ )

**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

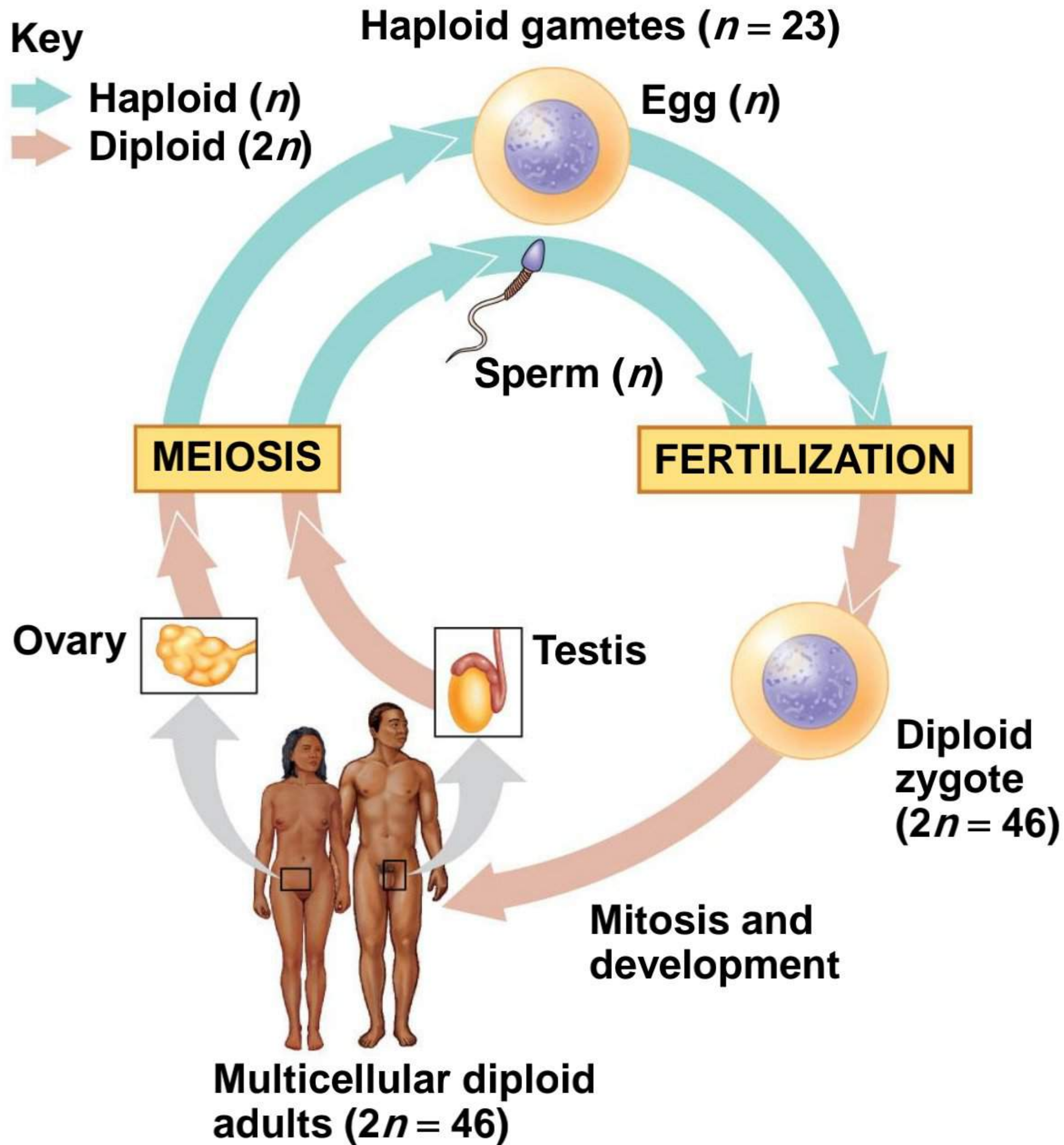
- **Fertilization** is the union of gametes (the sperm and the egg)
- The fertilized egg is called a **zygote** and has one set of chromosomes from each parent
- The zygote produces somatic cells by mitosis and develops into an adult



- 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 13.5





# 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



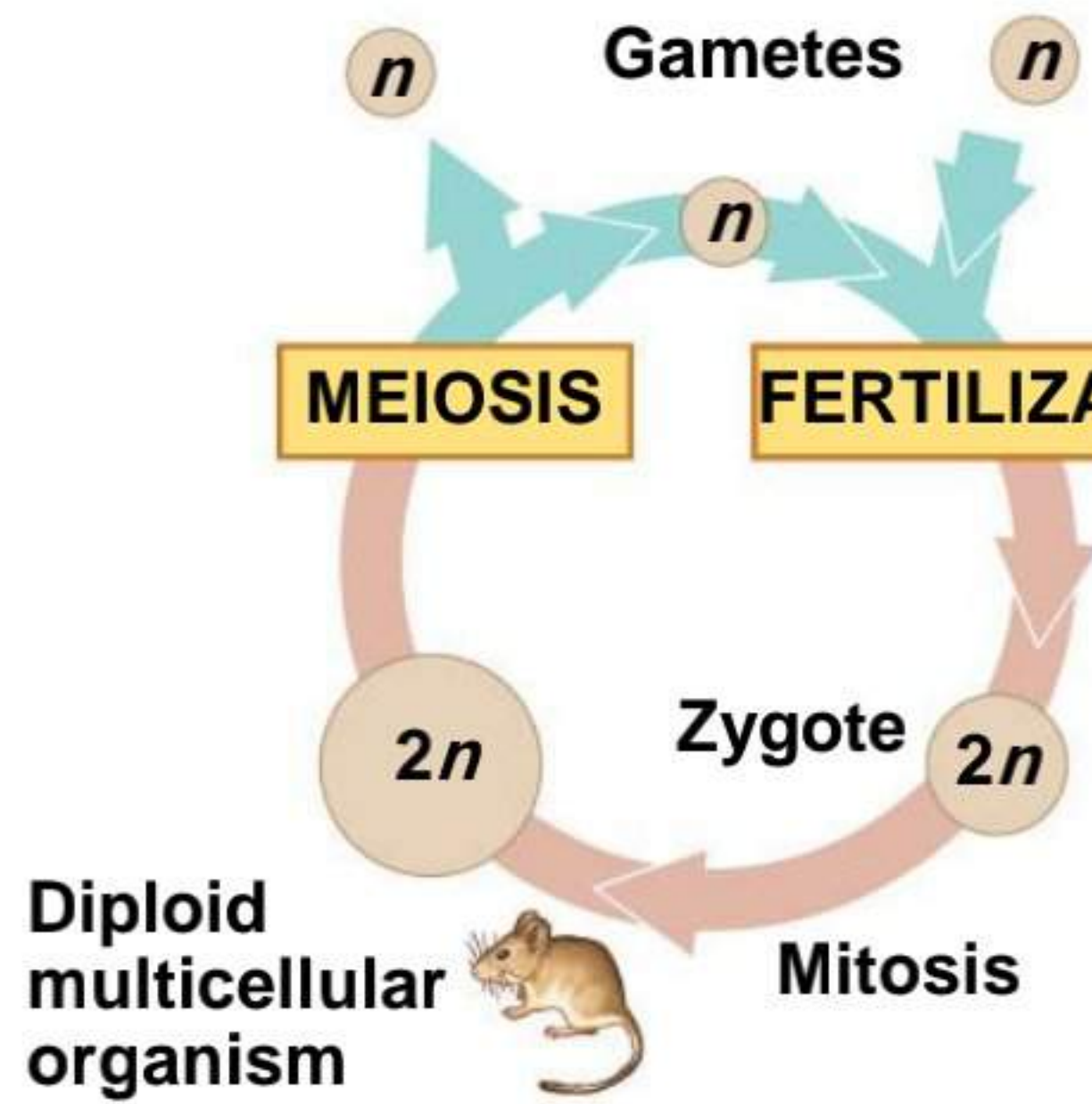
- Gametes are the only haploid cells in animals
- They are produced by meiosis and undergo no further cell division before fertilization
- Gametes fuse to form a diploid zygote that divides by mitosis to develop into a multicellular organism



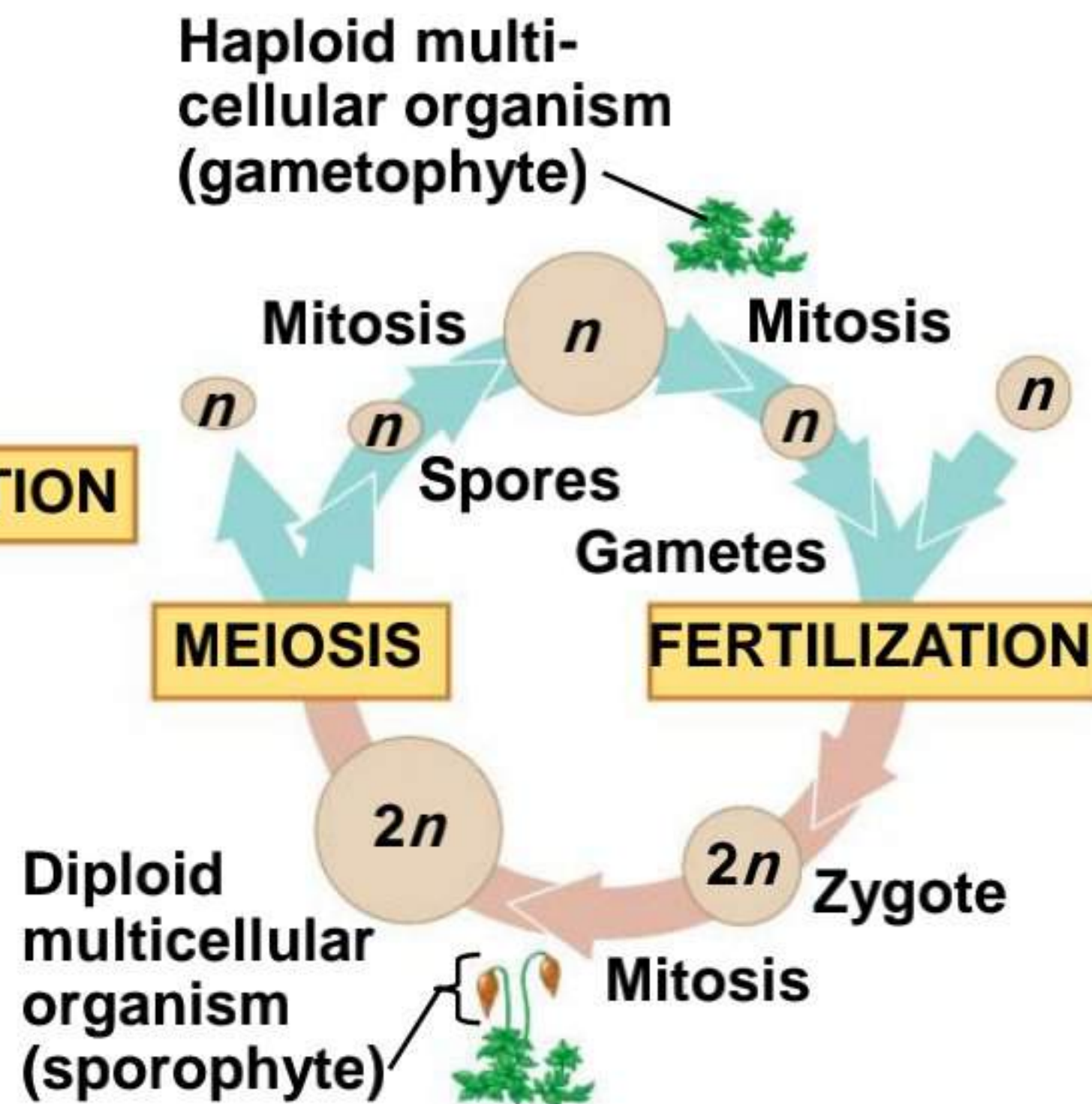
Figure 13.6

Key

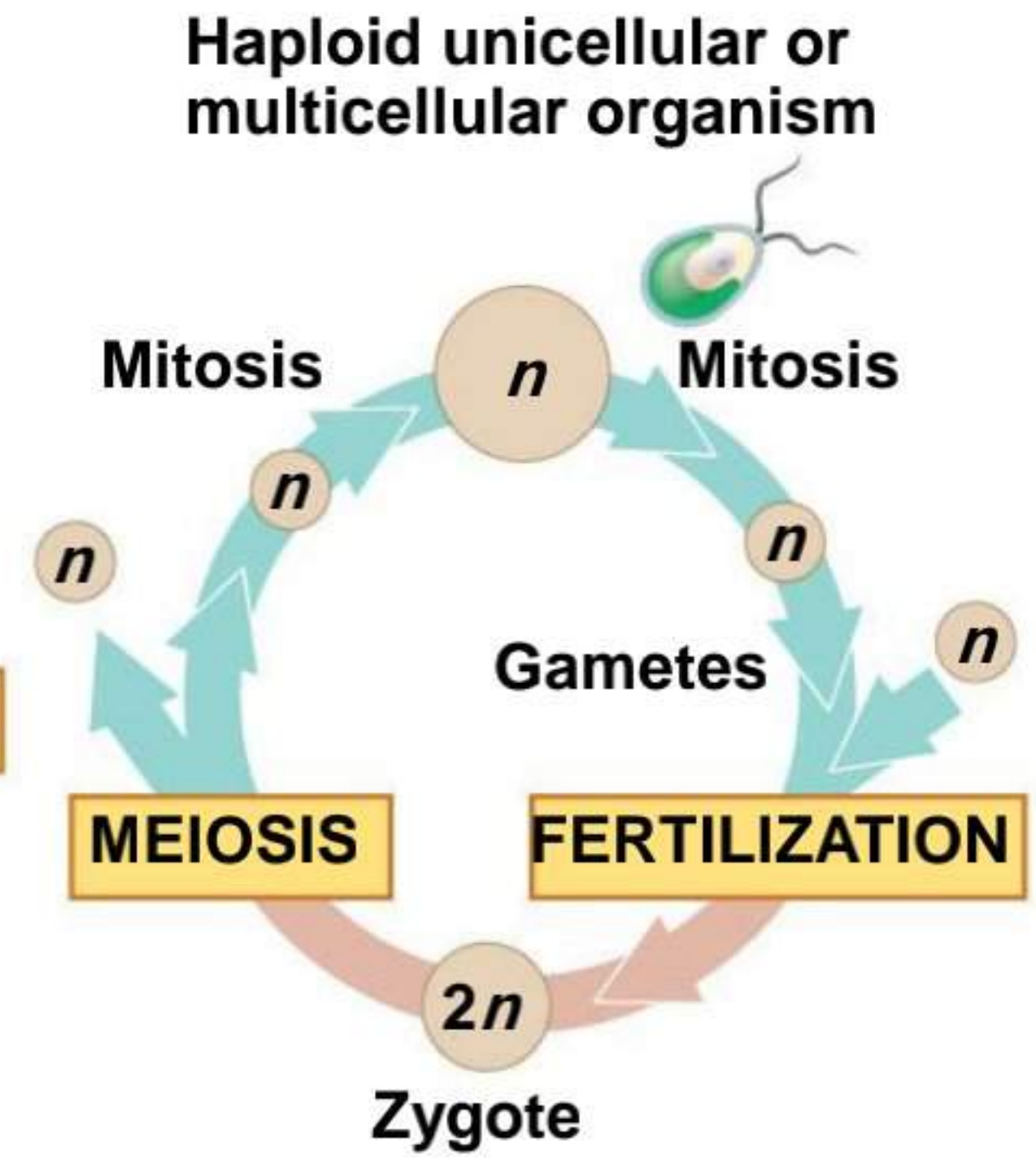
- ➡ Haploid ( $n$ )
- ➡ Diploid ( $2n$ )



(a) Animals



(b) Plants and some algae



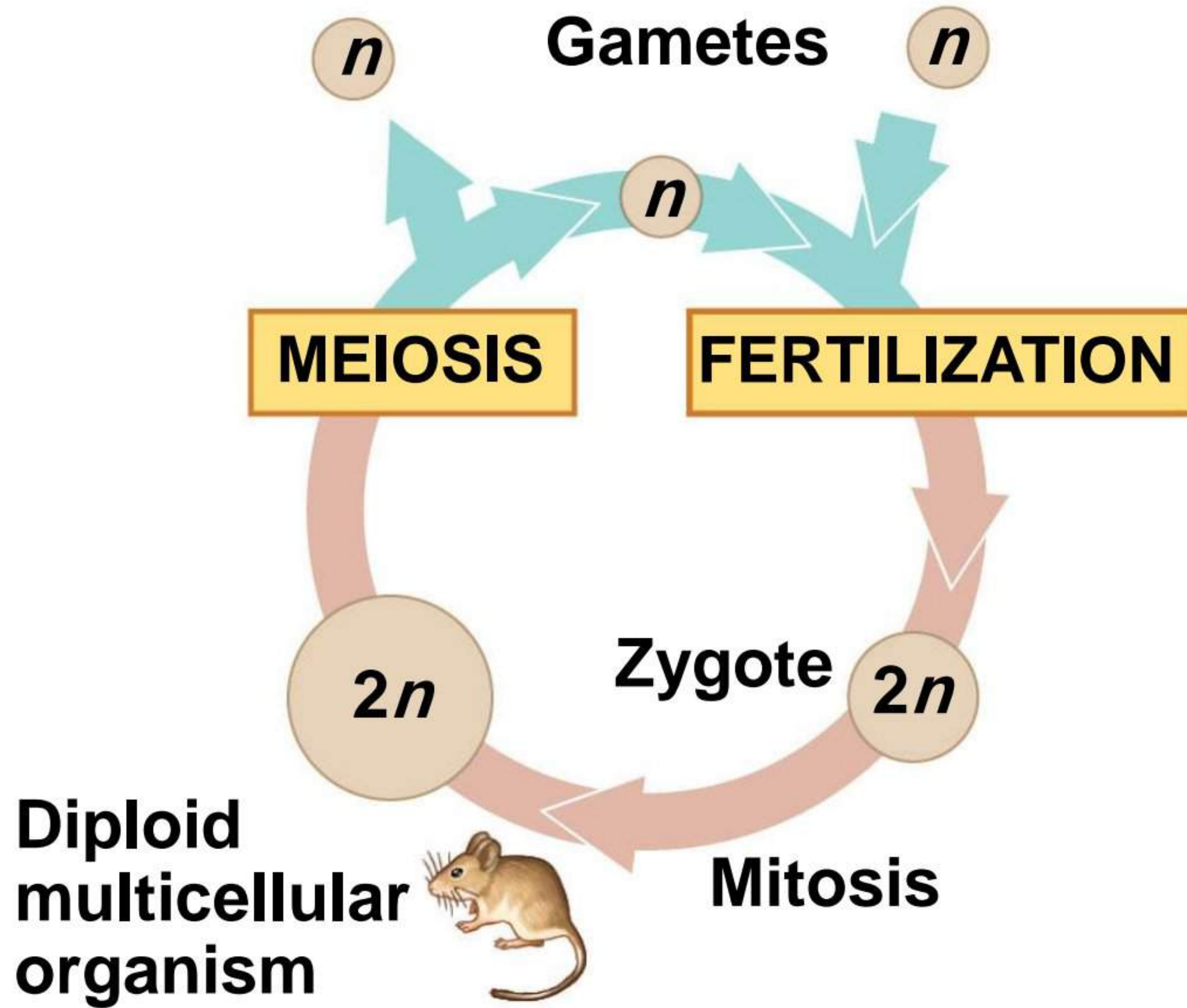
(c) Most fungi and some protists



Figure 13.6a

## Key

- Haploid ( $n$ )
- Diploid ( $2n$ )



## (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

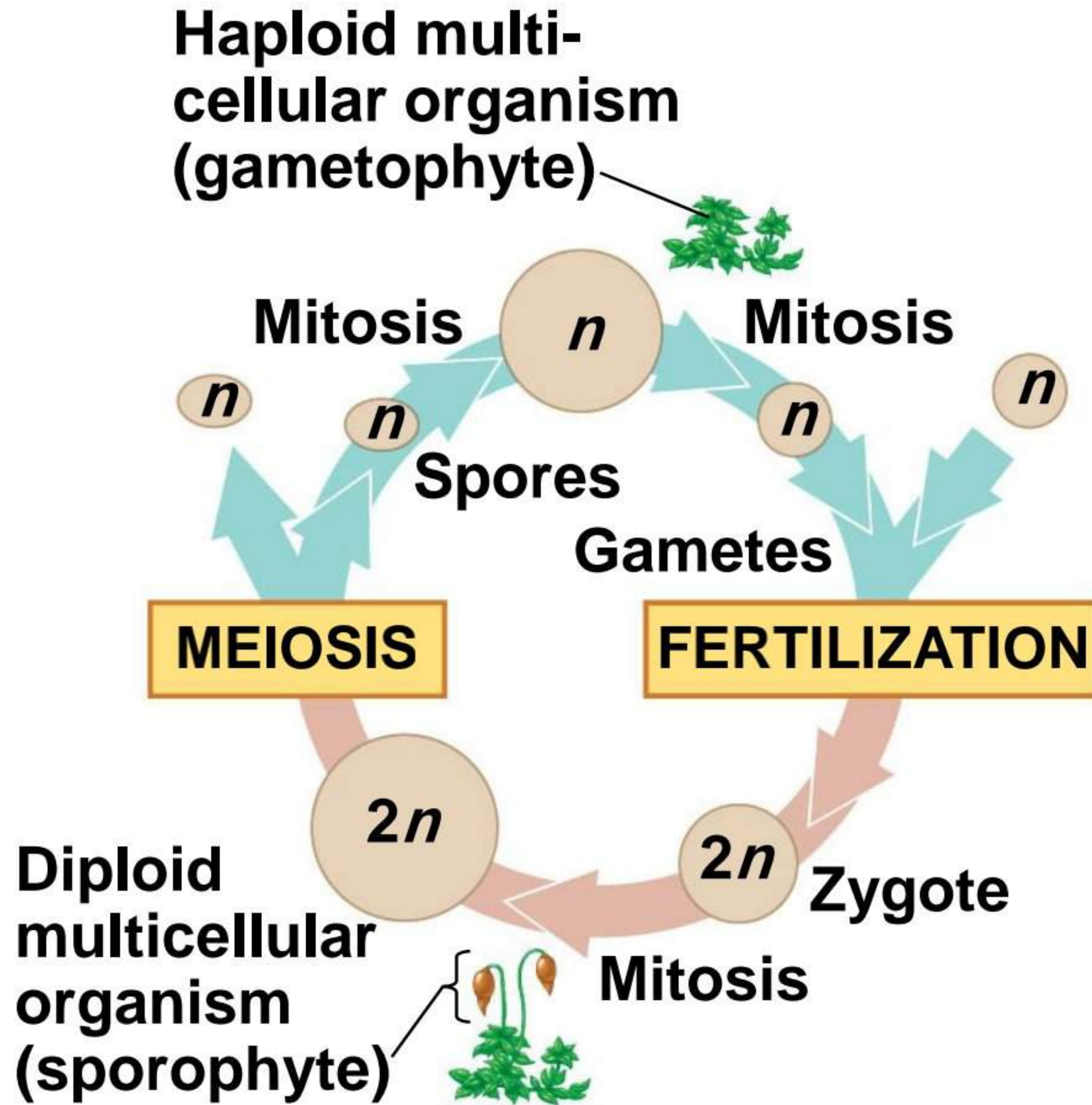


Figure 13.6b

**Key**

 Haploid ( $n$ )

 Diploid ( $2n$ )



**(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



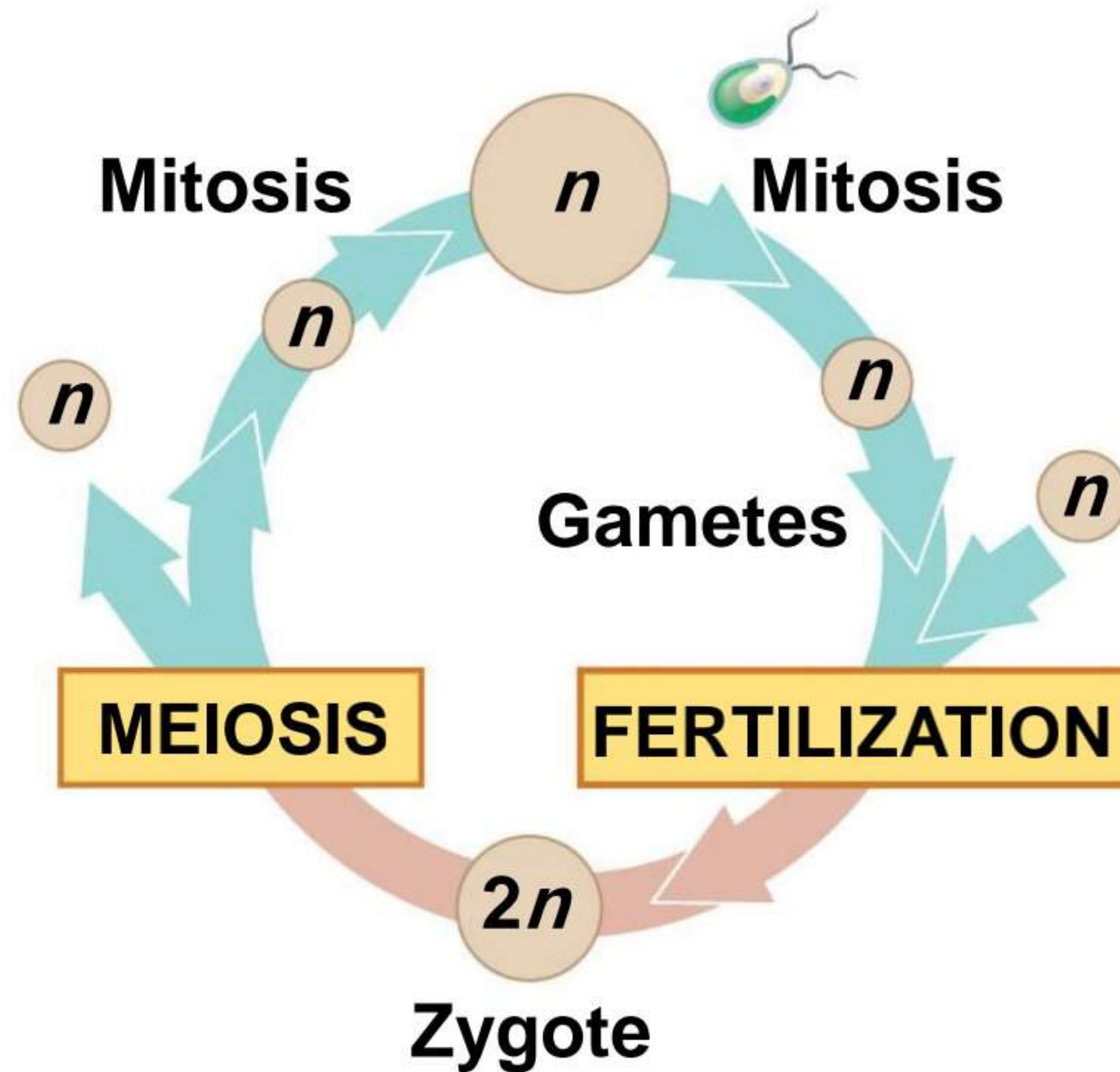
Figure 13.6c

## Key

→ Haploid ( $n$ )

→ Diploid ( $2n$ )

Haploid unicellular or multicellular organism



**(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 contributes to genetic variation in offspring



# Concept 13.3: Meiosis reduces the number of chromosome sets from diploid to haploid

- Like mitosis, meiosis is preceded by the replication 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

- After chromosomes duplicate, two divisions follow
  - Meiosis I (reductional division): homologs pair up and separate, resulting in two haploid daughter cells with replicated chromosomes
  - Meiosis II (equational division) sister chromatids separate
- The result is four haploid daughter cells with unreplicated chromosomes



Figure 13.7-1

## Interphase

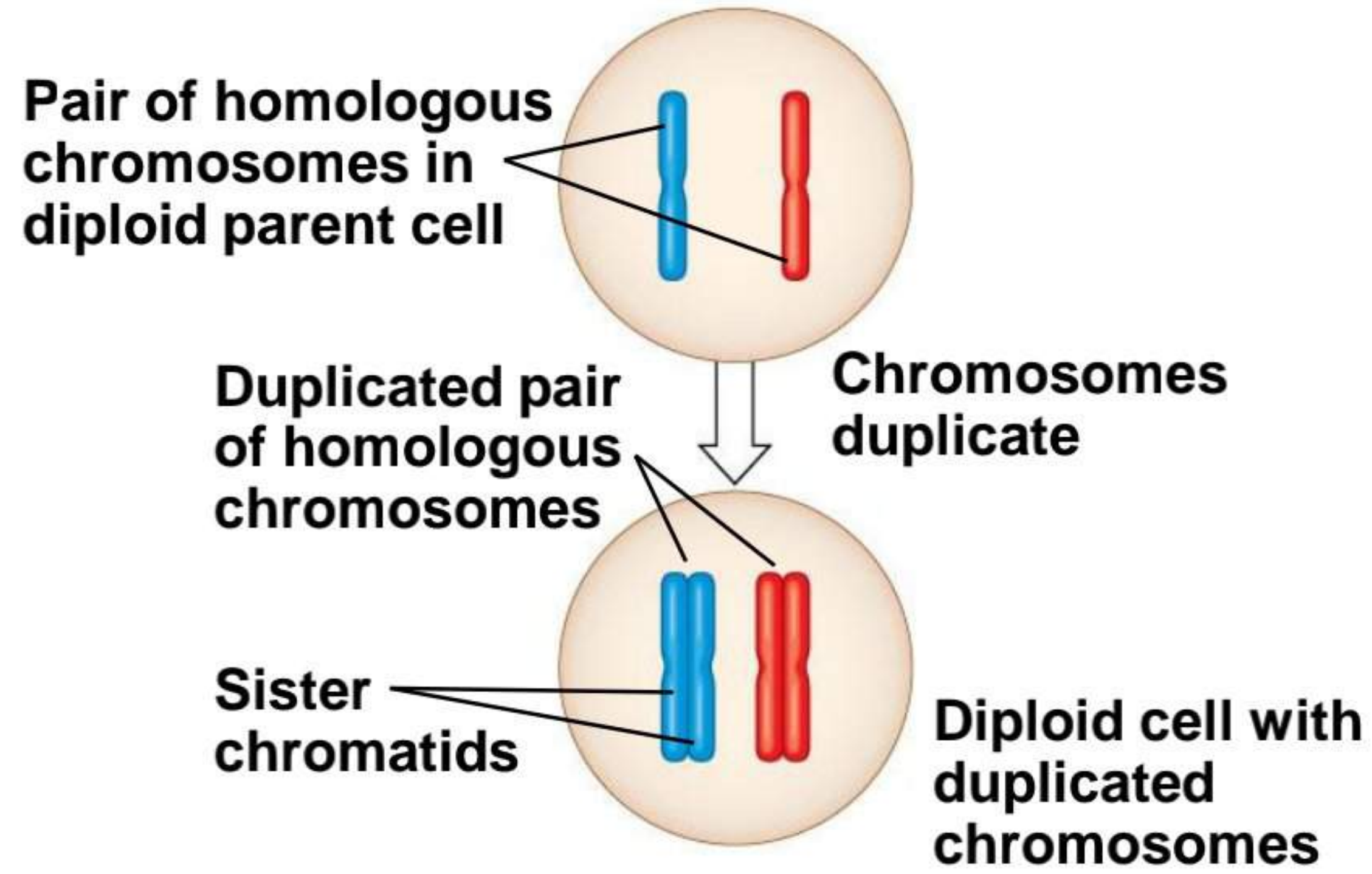




Figure 13.7-2

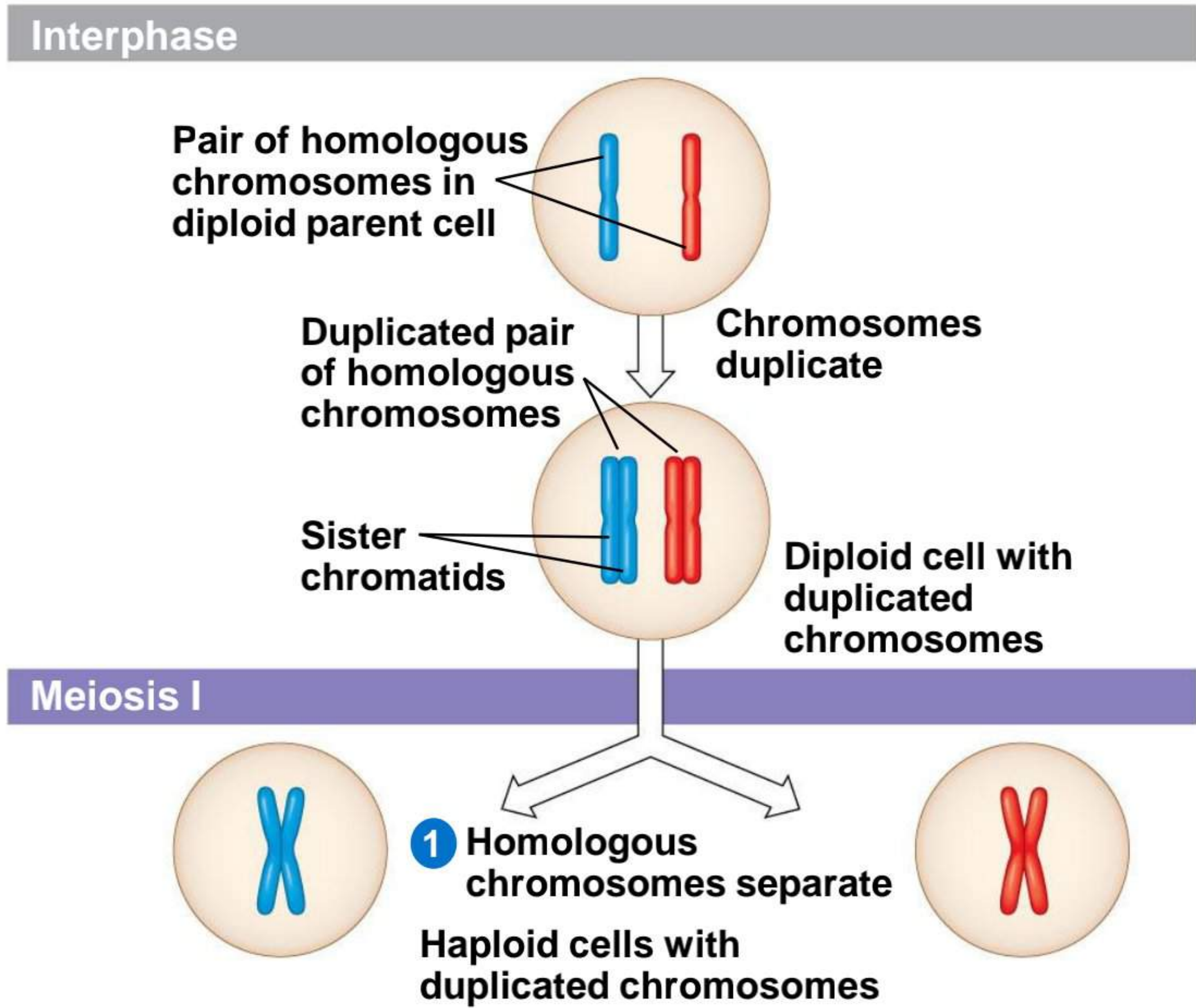
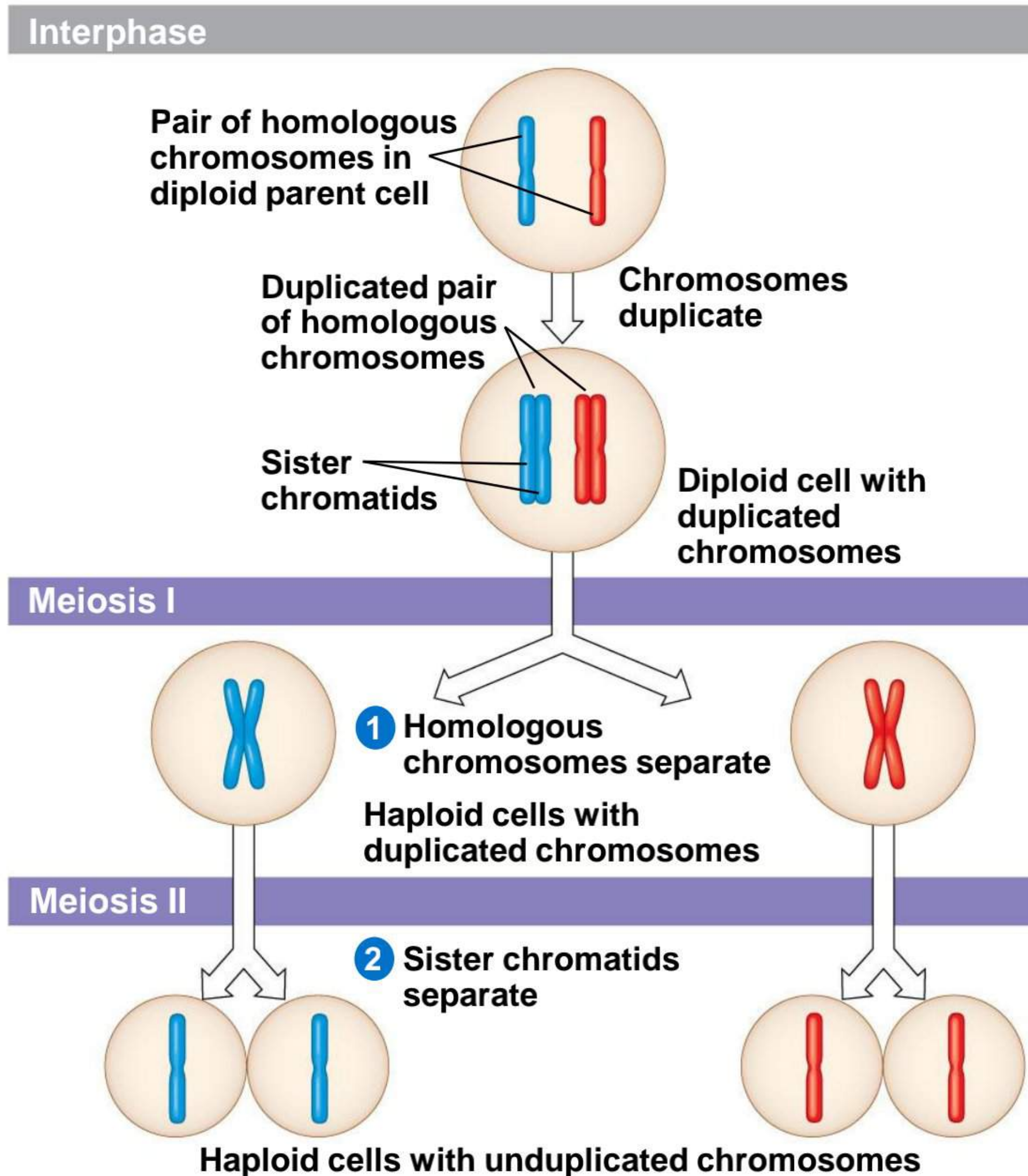




Figure 13.7-3





- Meiosis I is preceded by interphase, when the chromosomes are duplicated to form sister chromatids
- The sister chromatids are genetically identical and joined at the centromere
- The single centrosome replicates, forming two centrosomes



BioFlix: Meiosis



- Division in meiosis I occurs in four phases
  - Prophase I
  - Metaphase I
  - Anaphase I
  - Telophase I and cytokinesis



Figure 13.8

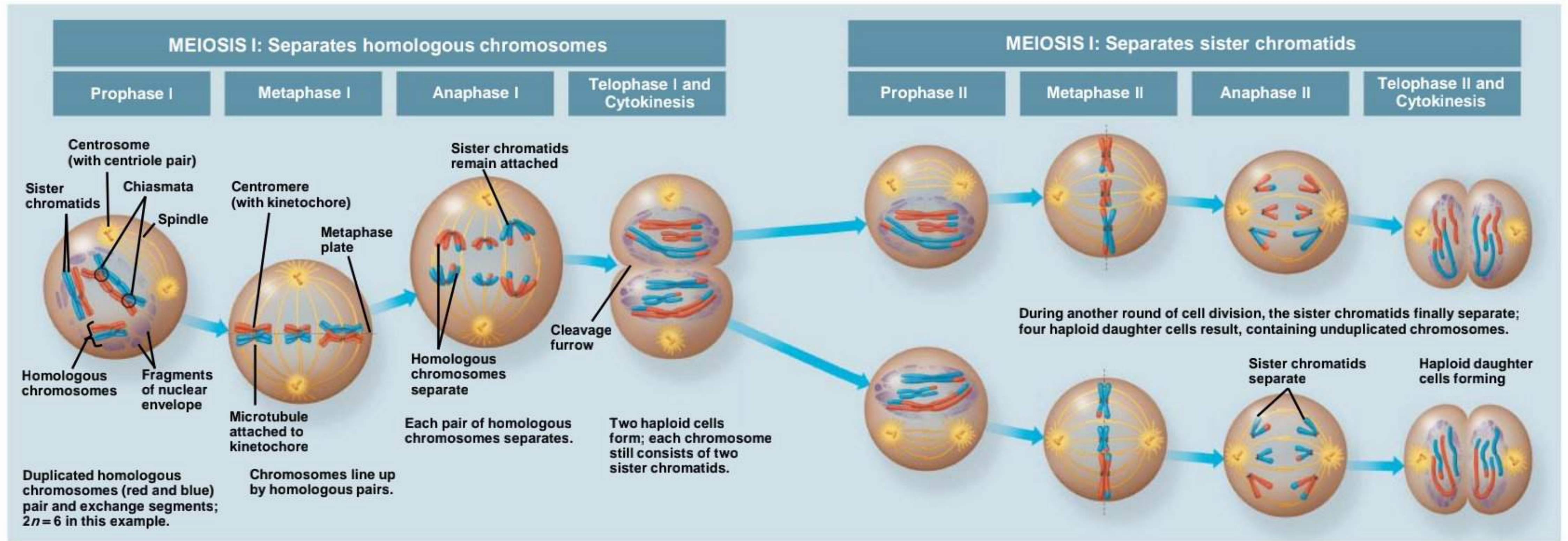
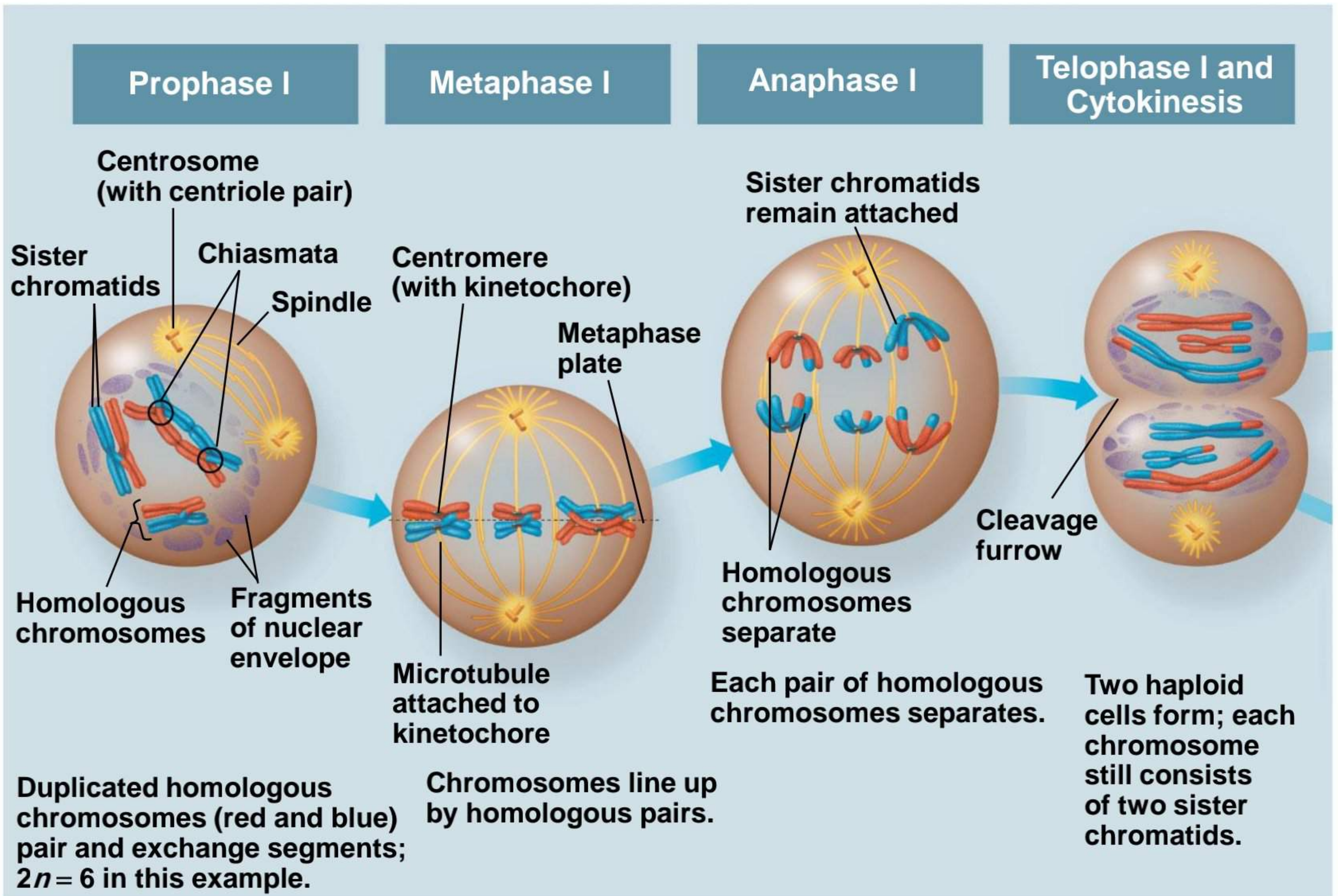




Figure 13.8a





# Prophase I

- Prophase I typically occupies more than 90% of the time required for meiosis
- Chromosomes begin to condense
- In **synapsis**, homologous chromosomes loosely pair up, aligned gene by gene



- In **crossing over**, nonsister chromatids exchange DNA segments
- Each pair of chromosomes forms a tetrad, a group of four chromatids
- Each tetrad usually has one or more **chiasmata**, X-shaped regions where crossing over occurred



## Metaphase I

- In metaphase I, tetrads 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



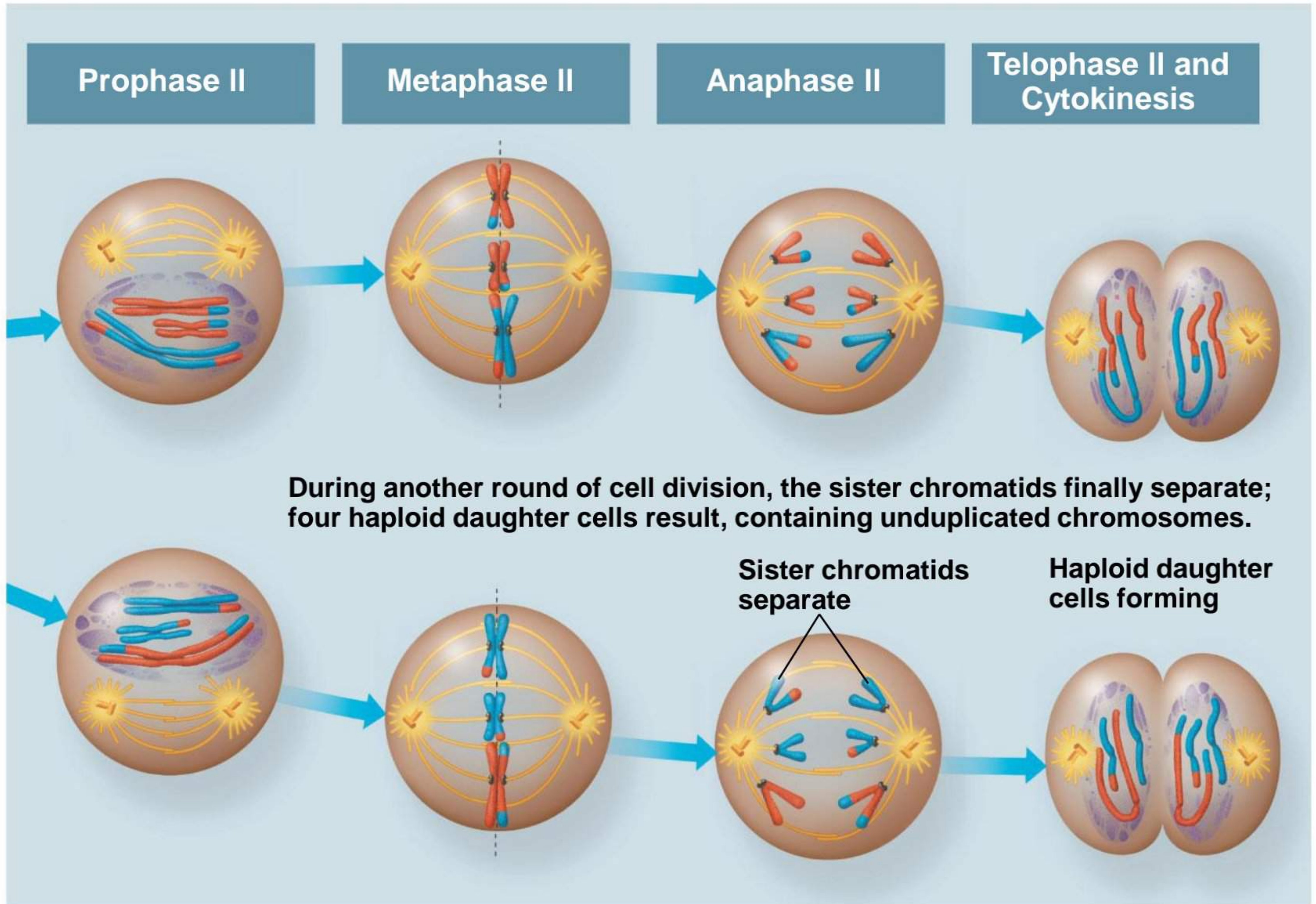
- In animal cells, a cleavage furrow forms; in plant cells, a cell plate forms
- No chromosome replication occurs between the end of meiosis I and the beginning of meiosis II because the chromosomes are already replicated



- 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



Figure 13.8b





## 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

- In 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**

- In telophase II, the chromosomes arrive at opposite poles
- Nuclei form, and the chromosomes begin decondensing



- Cytokinesis separates the cytoplasm
- At the end of meiosis, there are four daughter cells, each with a haploid set of unreplicated chromosomes
- Each daughter cell is genetically distinct from the others and from the parent cell

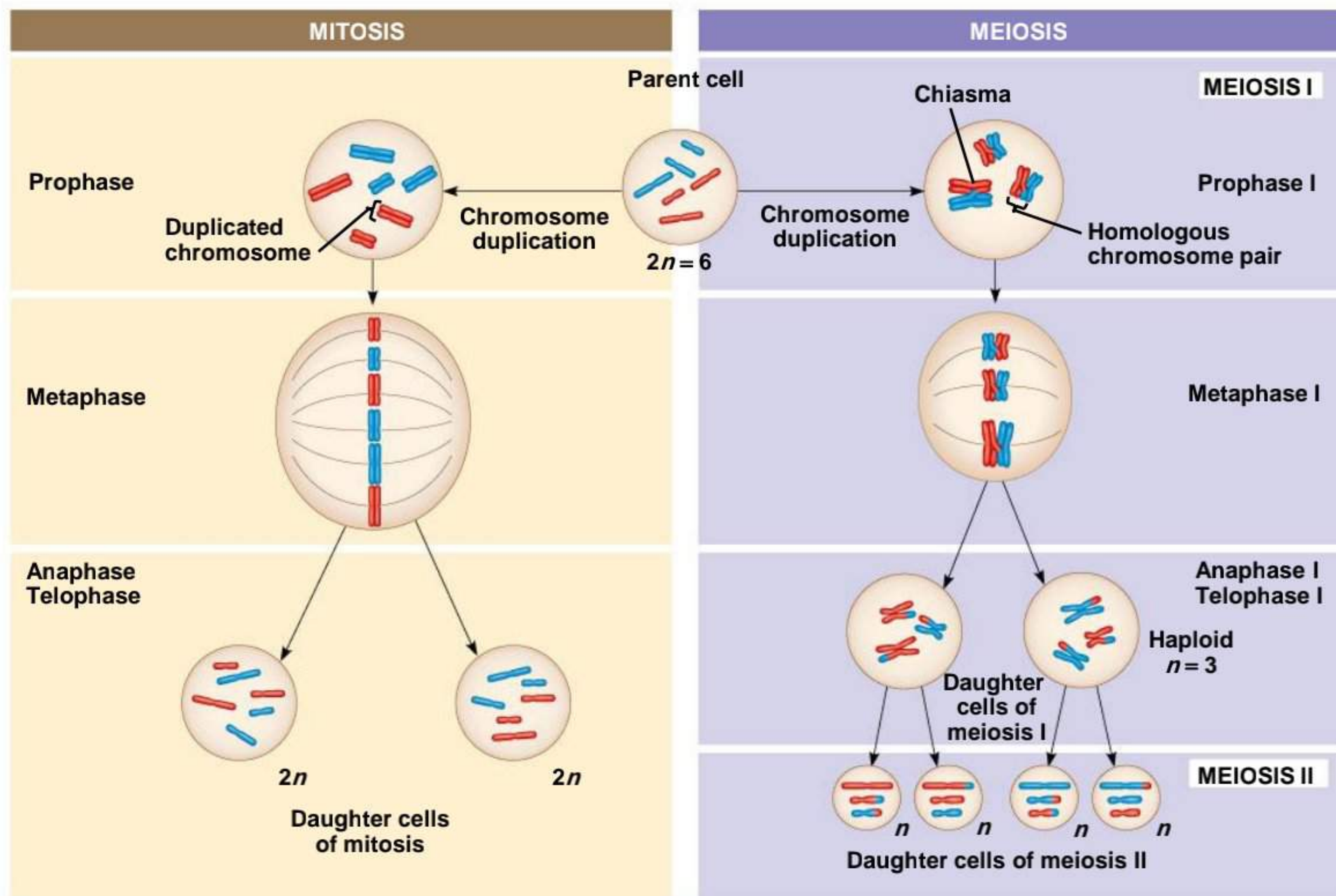


# A Comparison of Mitosis and Meiosis

- 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



Figure 13.9



**SUMMARY**

Property	Mitosis	Meiosis
<b>DNA replication</b>	Occurs during interphase before mitosis begins	Occurs during interphase before meiosis I begins
<b>Number of divisions</b>	One, including prophase, metaphase, anaphase, and telophase	Two, each including prophase, metaphase, anaphase, and telophase
<b>Synapsis of homologous chromosomes</b>	Does not occur	Occurs during prophase I along with crossing over between nonsister chromatids; resulting chiasmata hold pairs together due to sister chromatid cohesion
<b>Number of daughter cells and genetic composition</b>	Two, each diploid ( $2n$ ) and genetically identical to the parent cell	Four, each haploid ( $n$ ), containing half as many chromosomes as the parent cell; genetically different from the parent cell and from each other
<b>Role in the animal body</b>	Enables multicellular adult to arise from zygote; produces cells for growth, repair, and, in some species, asexual reproduction	Produces gametes; reduces number of chromosomes by half and introduces genetic variability among the gametes



Figure 13.9a

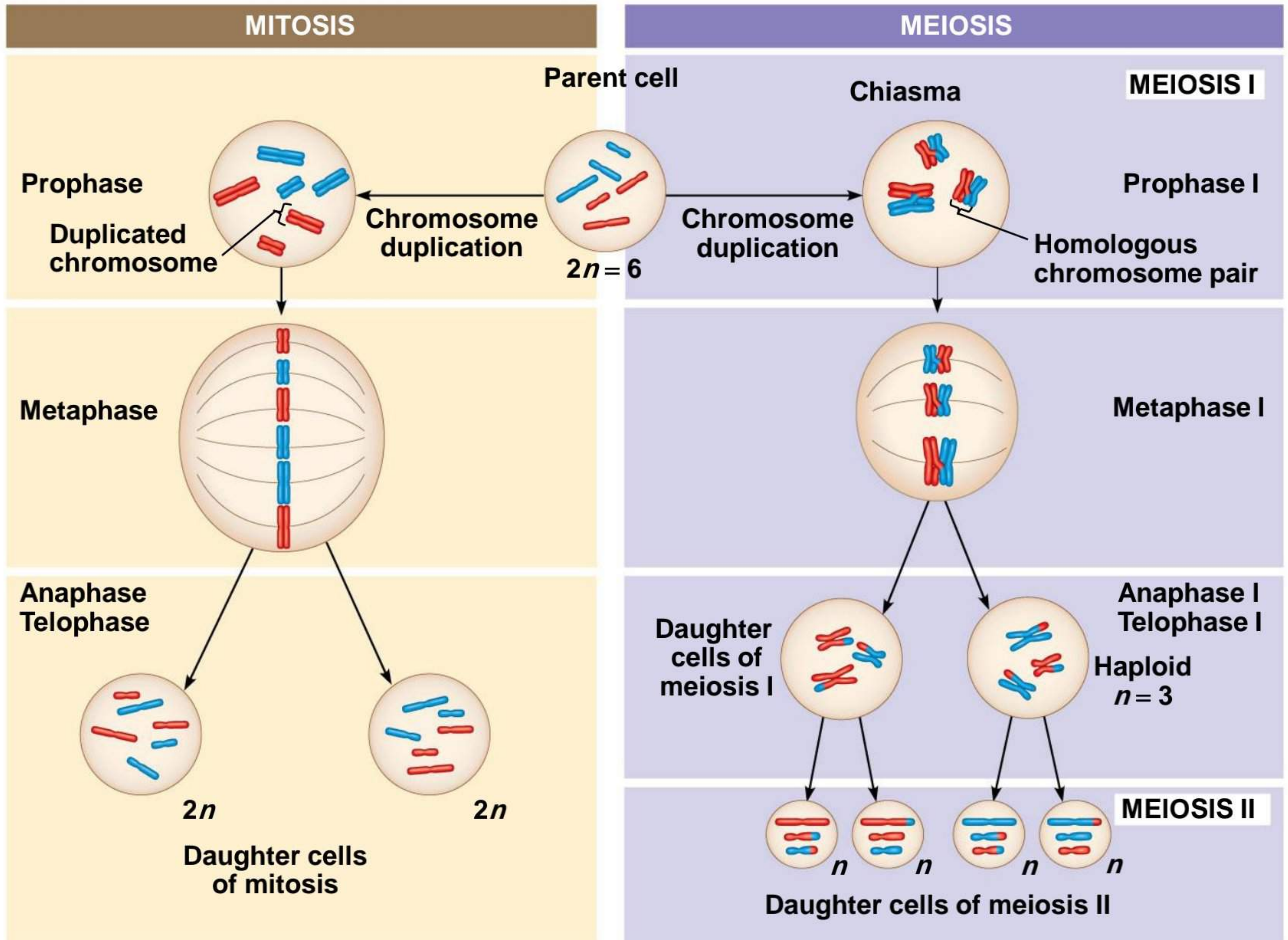




Figure 13.9b

SUMMARY		
Property	Mitosis	Meiosis
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- 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
  - At the metaphase plate, there are paired homologous chromosomes (tetrads), instead of individual replicated chromosomes
  - At anaphase I, it is homologous chromosomes, instead of sister chromatids, that separate



- Sister chromatid cohesion allows sister chromatids of a single chromosome to stay together through meiosis I
- Protein complexes called cohesins are responsible for this 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)



# **Concept 13.4: 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*

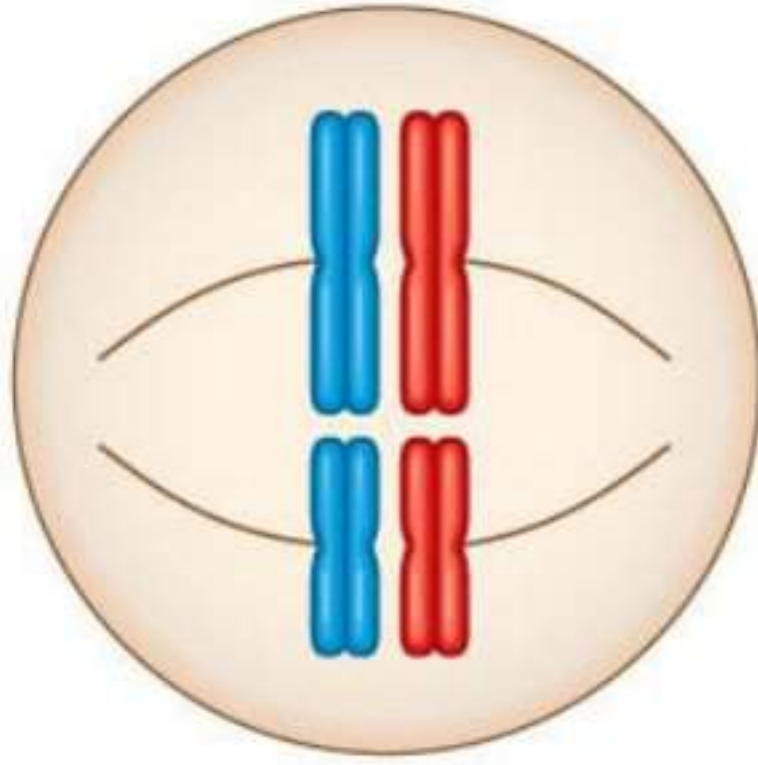
- Homologous pairs of chromosomes orient randomly at metaphase I of meiosis
- In independent assortment, each pair of chromosomes sorts maternal and paternal homologs into daughter cells independently of the other pairs



- 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

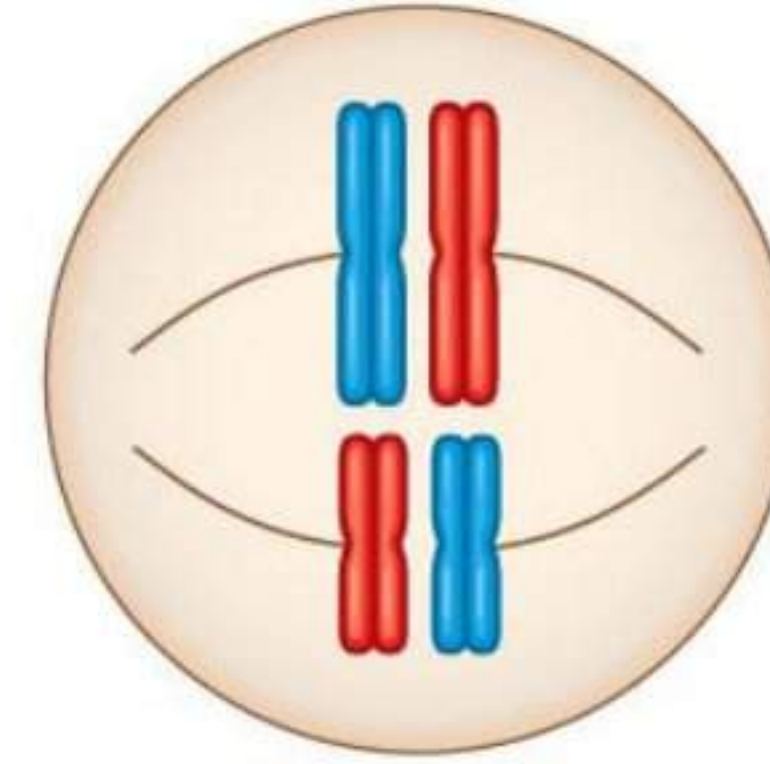


**Possibility 1**



**Two equally probable  
arrangements of  
chromosomes at  
metaphase I**

**Possibility 2**





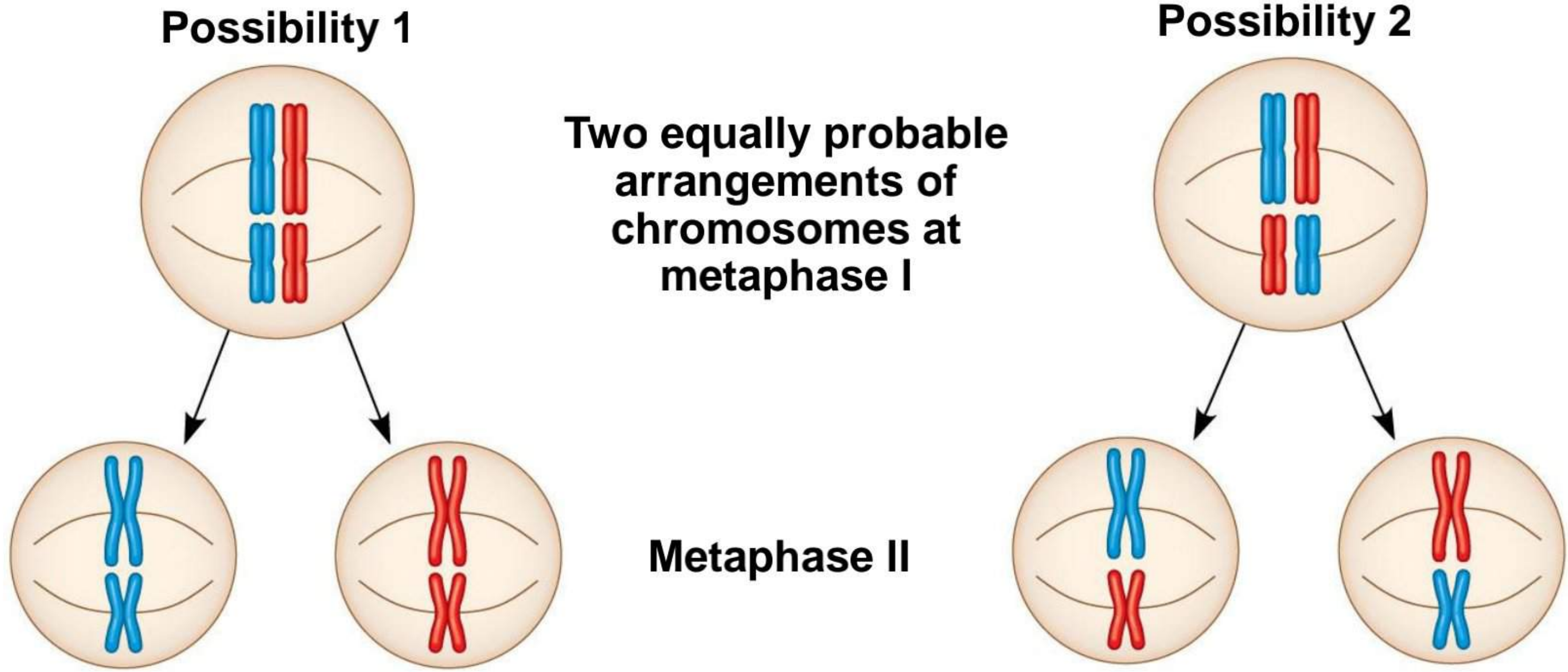
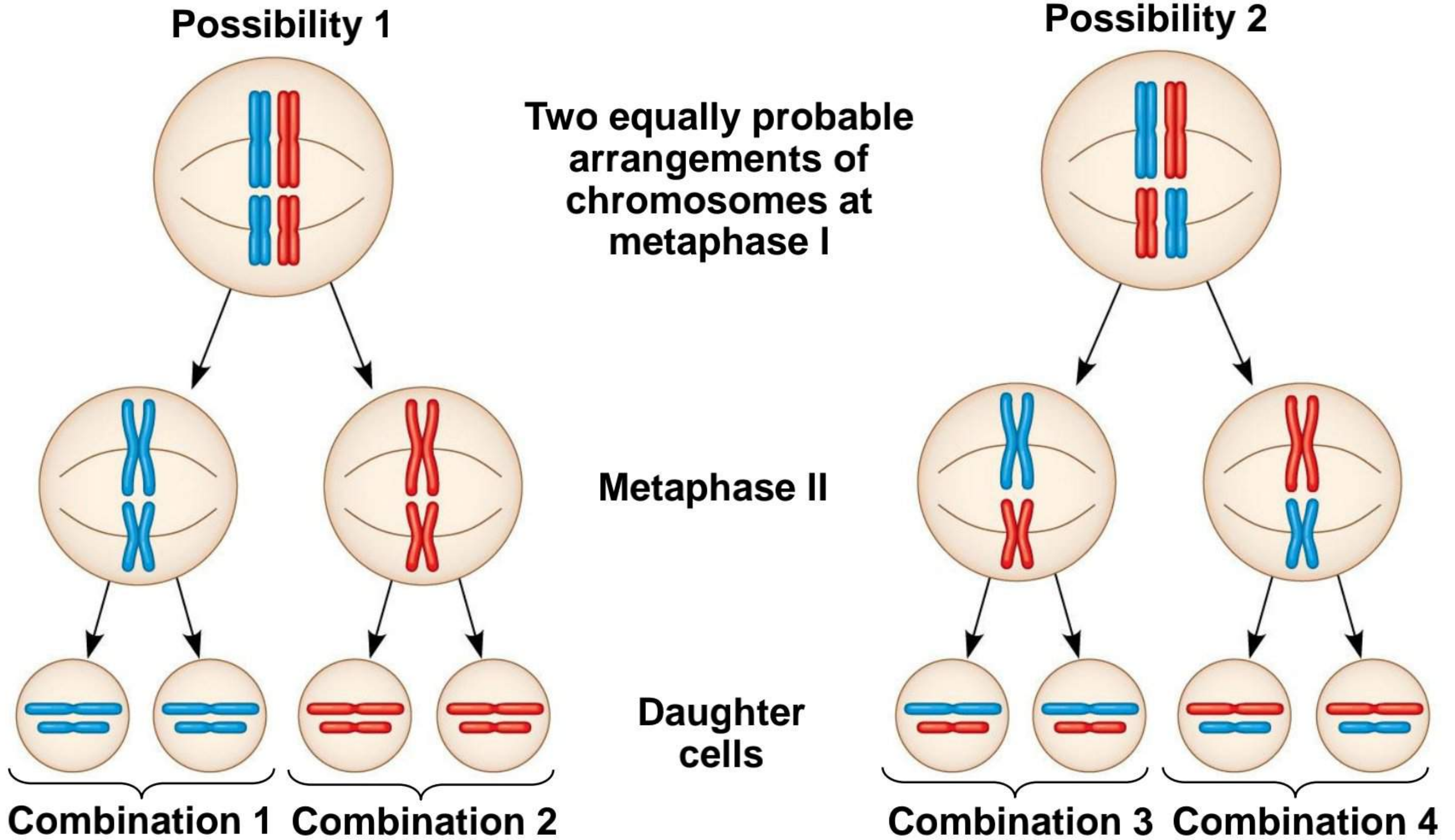




Figure 13.10-3





# *Crossing Over*

- Crossing over produces **recombinant chromosomes**, which combine DNA inherited from each parent
- Crossing over begins very early in prophase I, as homologous chromosomes pair up gene by gene



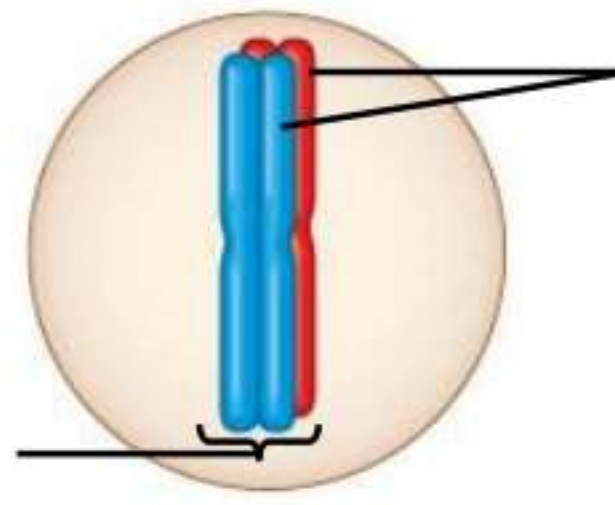
- In crossing over, homologous portions of two nonsister chromatids trade places
- Crossing over contributes to genetic variation by combining DNA from two parents into a single chromosome



Figure 13.11-1

# Prophase I of meiosis

Pair of homologs



Nonsister chromatids  
held together  
during synapsis



Figure 13.11-2

# Prophase I of meiosis

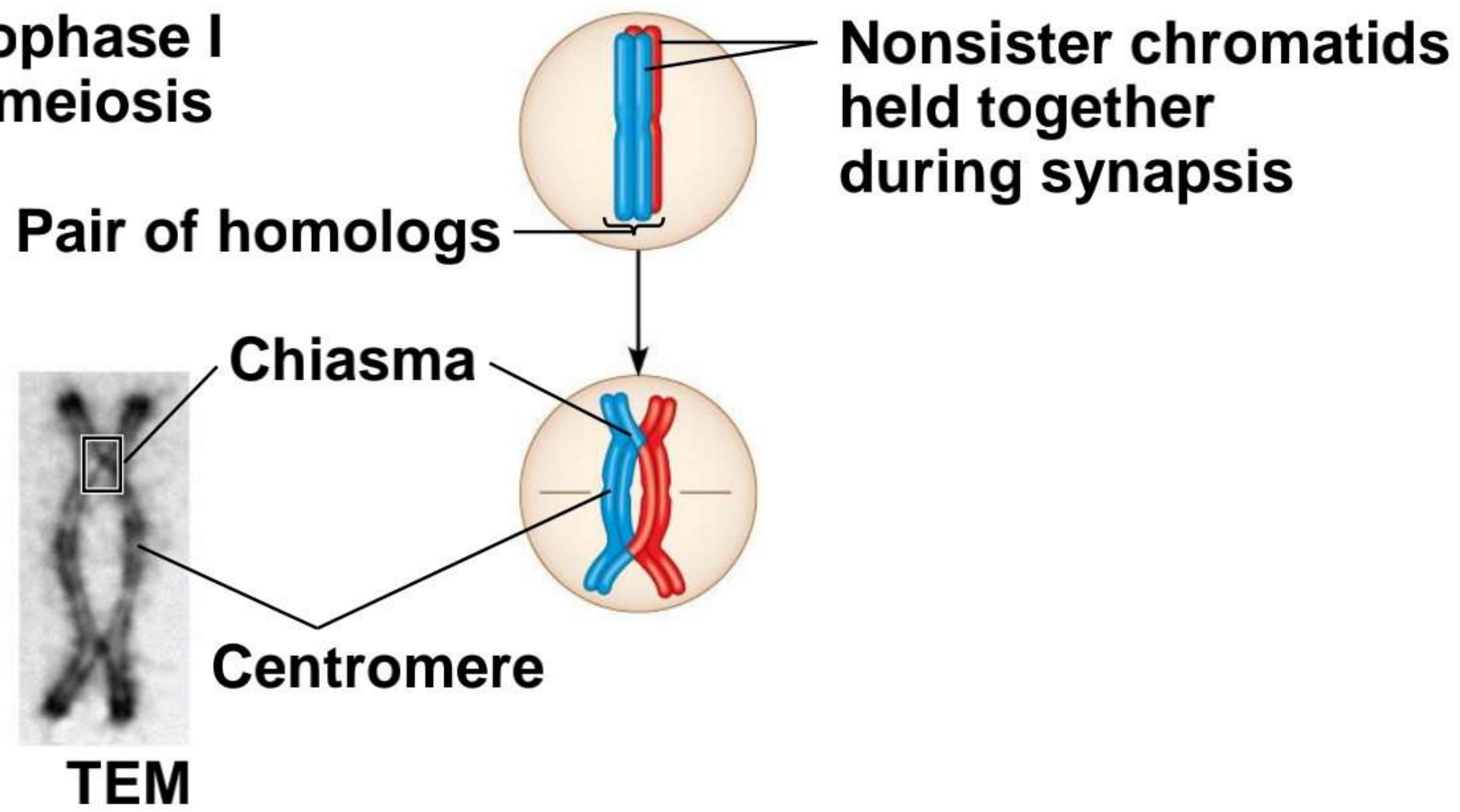


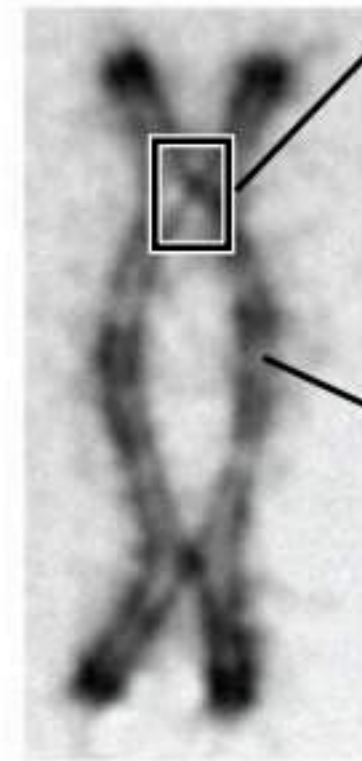


Figure 13.11-3

# Prophase I of meiosis

**Nonsister chromatids  
held together  
during synapsis**

**Pair of homologs**



**Chiasma**

**Centromere**

**TEM**

# Anaphase I

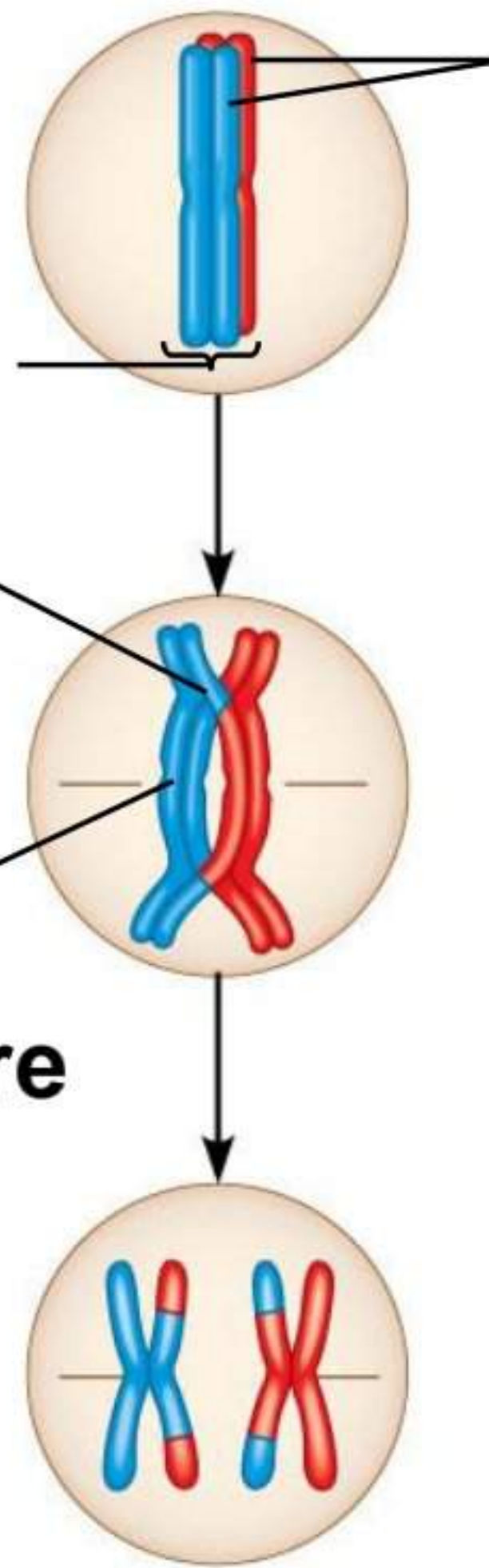


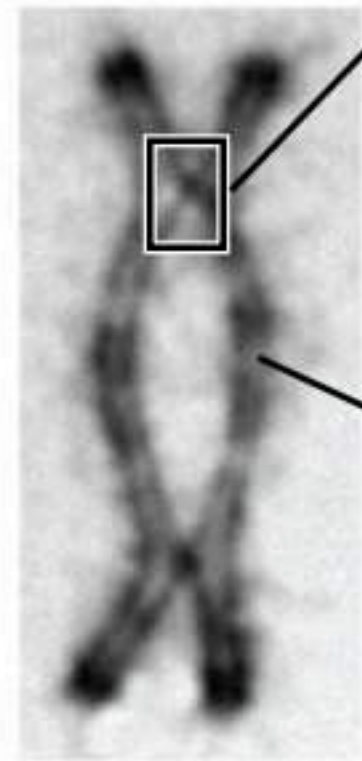


Figure 13.11-4

# Prophase I of meiosis

**Nonsister chromatids  
held together  
during synapsis**

**Pair of homologs**



**Chiasma**

**Centromere**

**TEM**

# Anaphase I

# Anaphase II

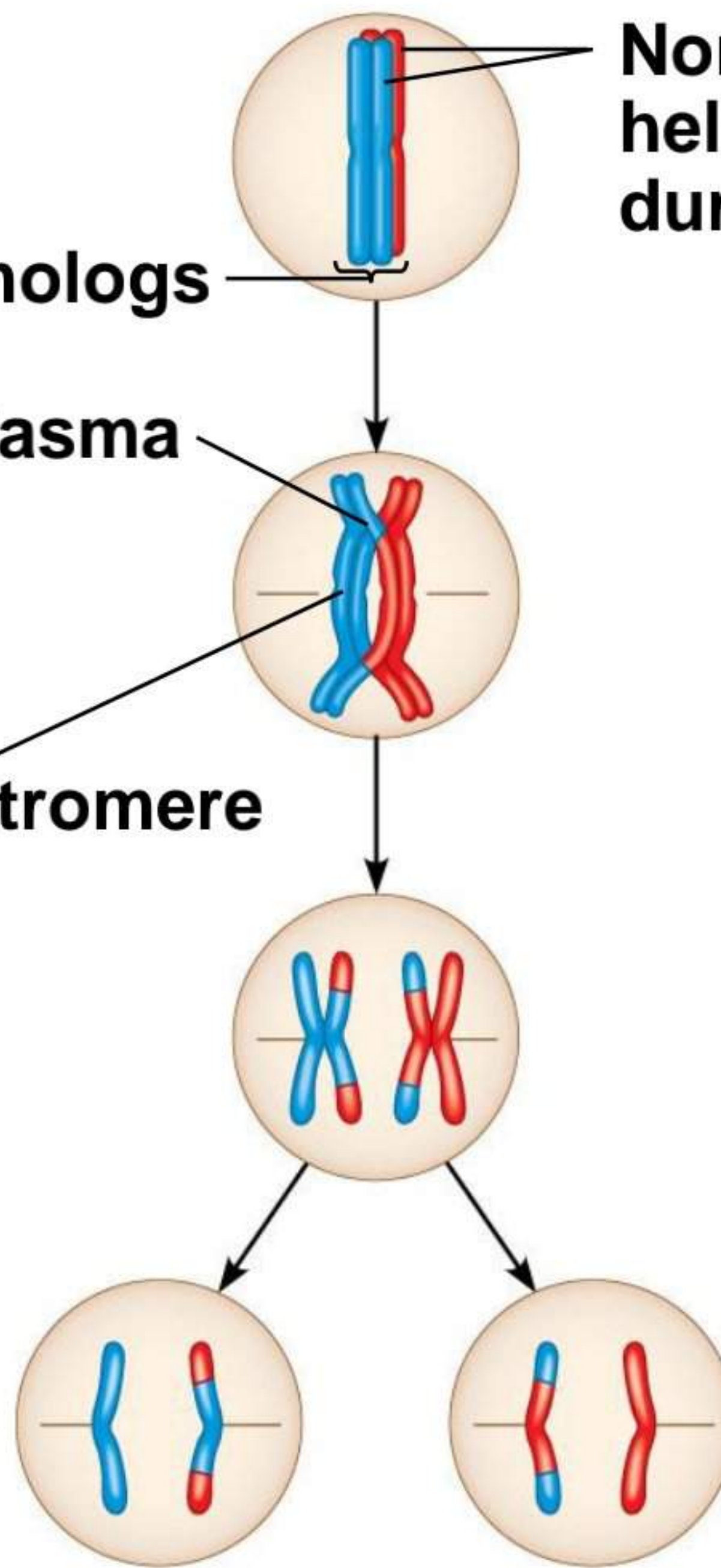


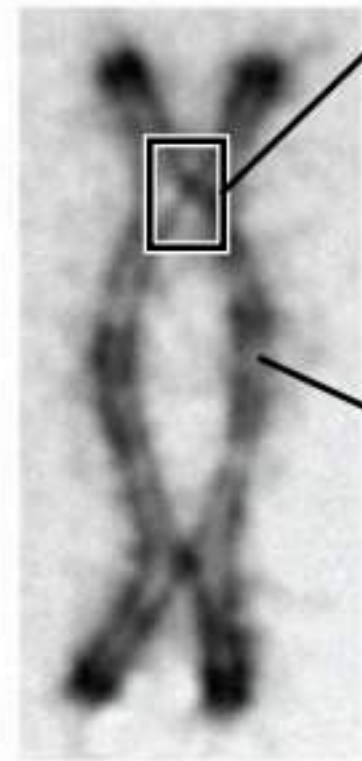


Figure 13.11-5

# Prophase I of meiosis

**Nonsister chromatids  
held together  
during synapsis**

**Pair of homologs**



**Chiasma**

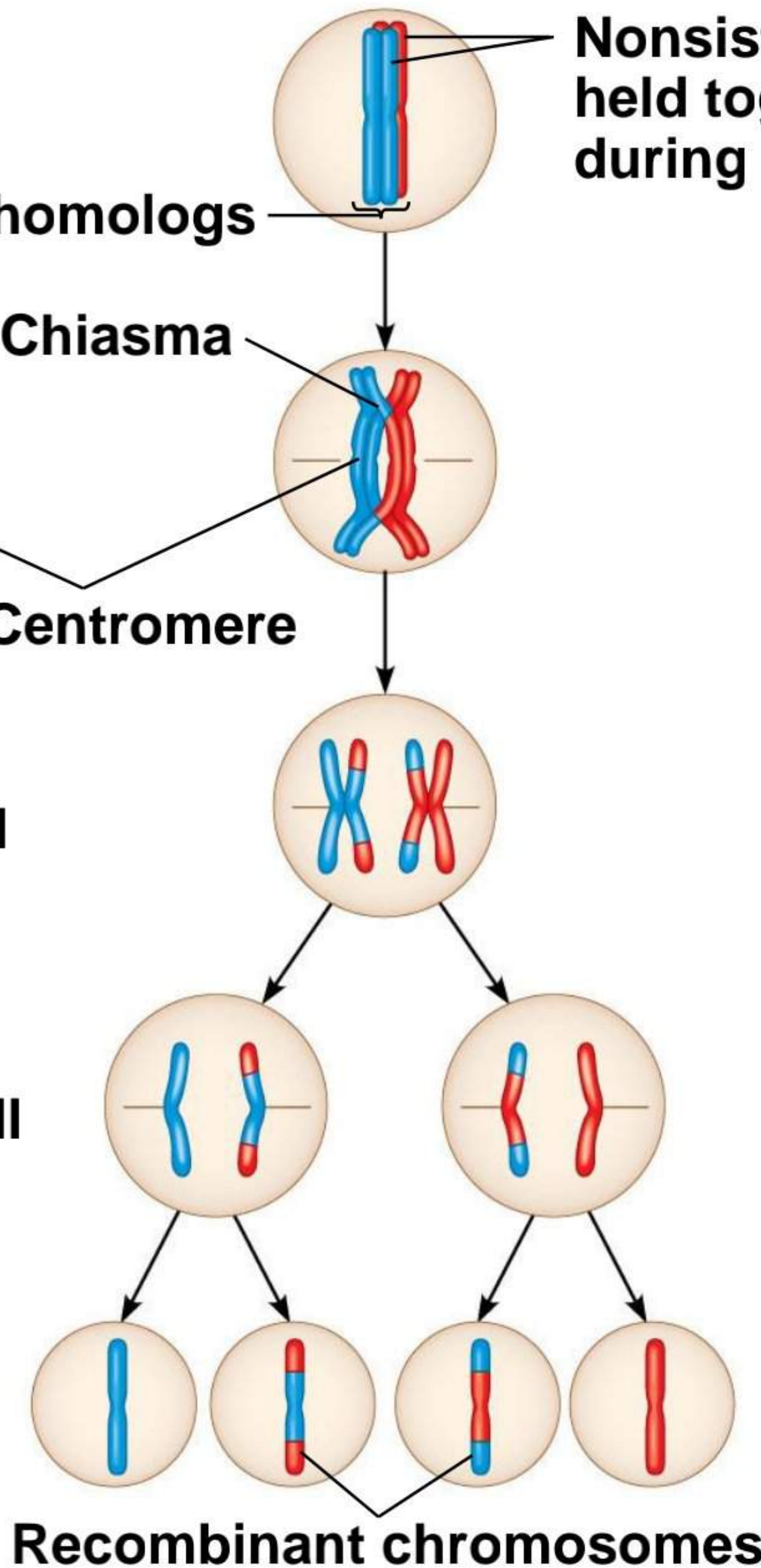
**Centromere**

**TEM**

# Anaphase I

# Anaphase II

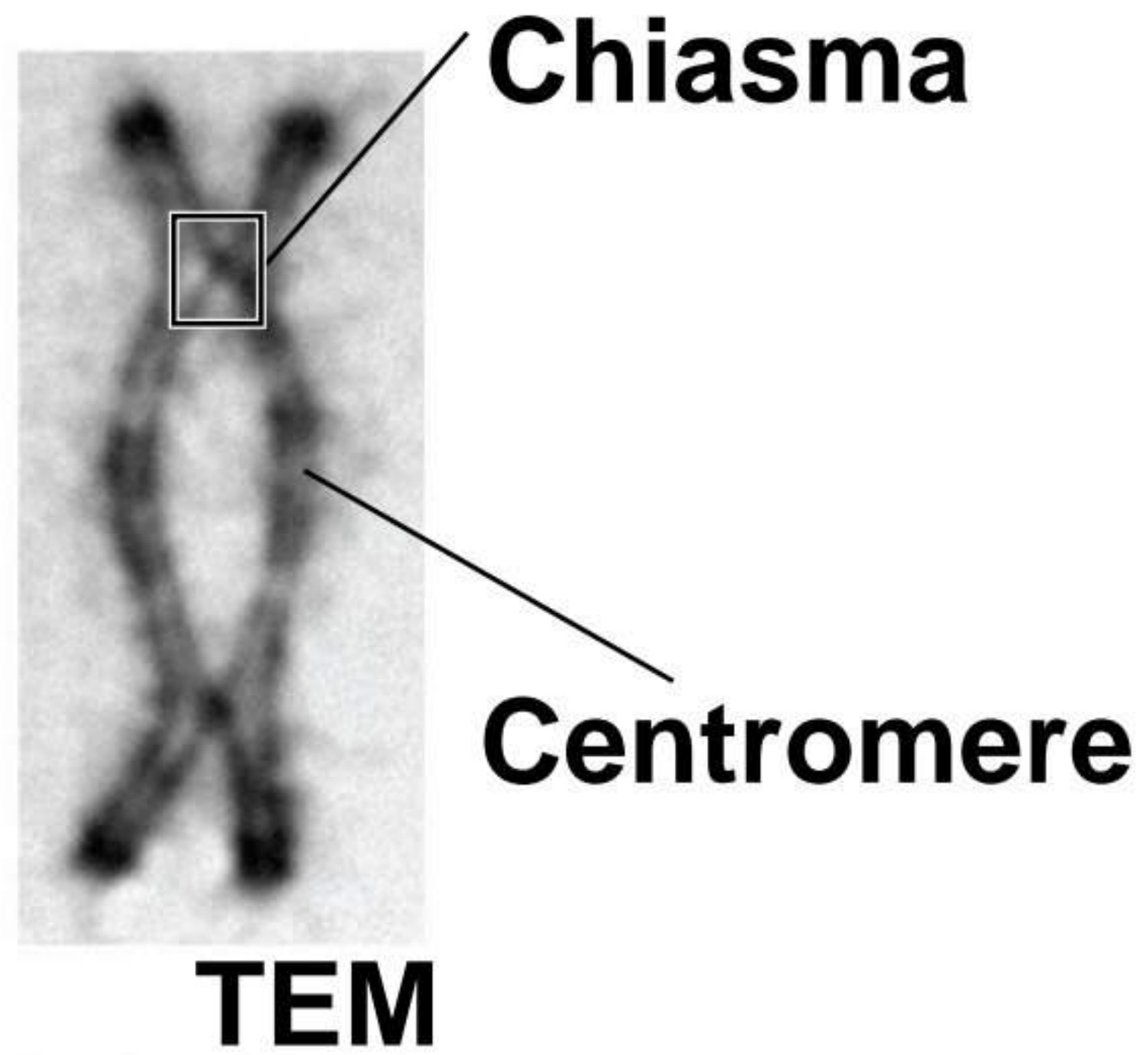
**Daughter  
cells**



**Recombinant chromosomes**



Figure 13.11a



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# *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



Animation: Genetic Variation

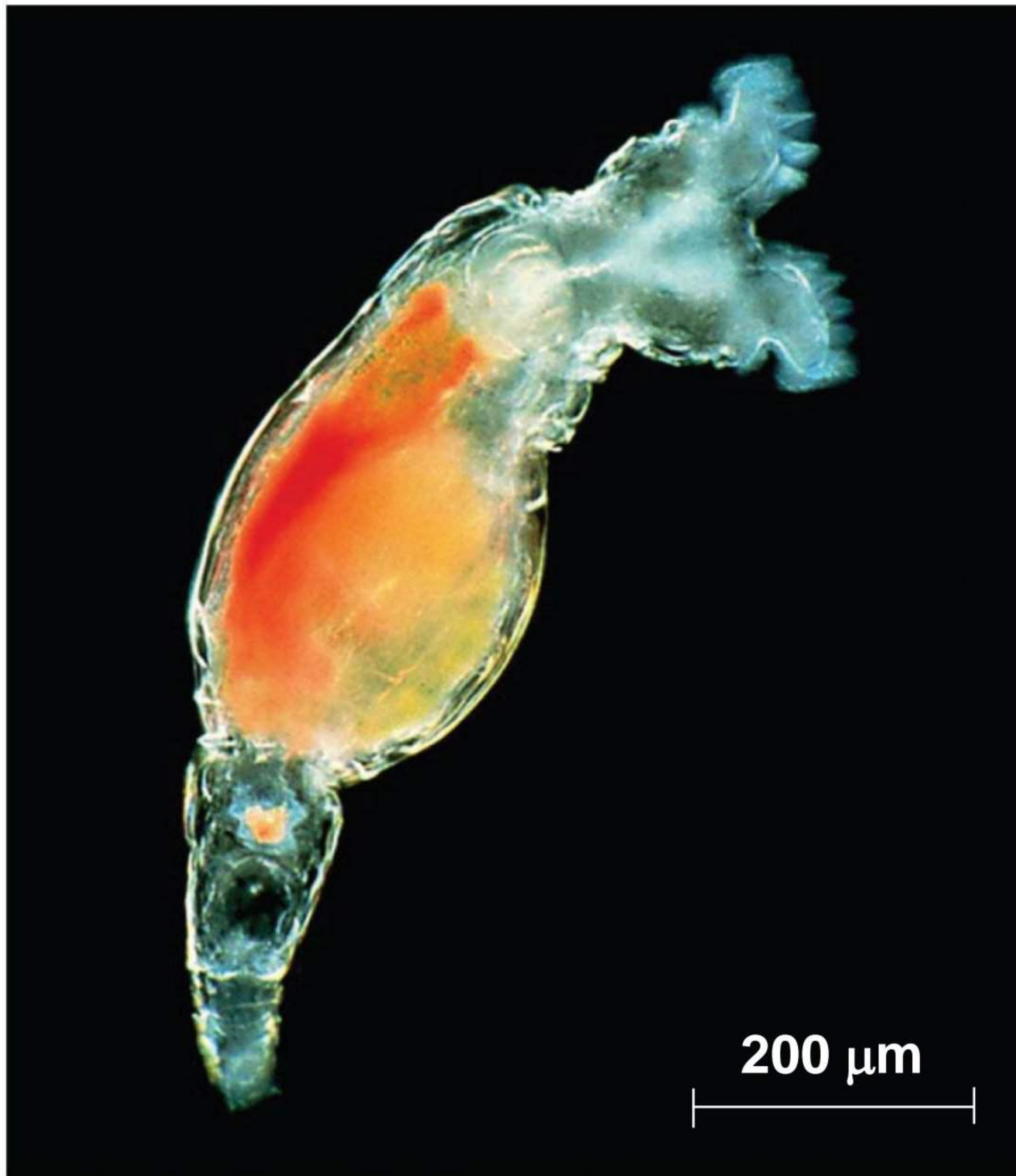


# The Evolutionary Significance of Genetic Variation Within Populations

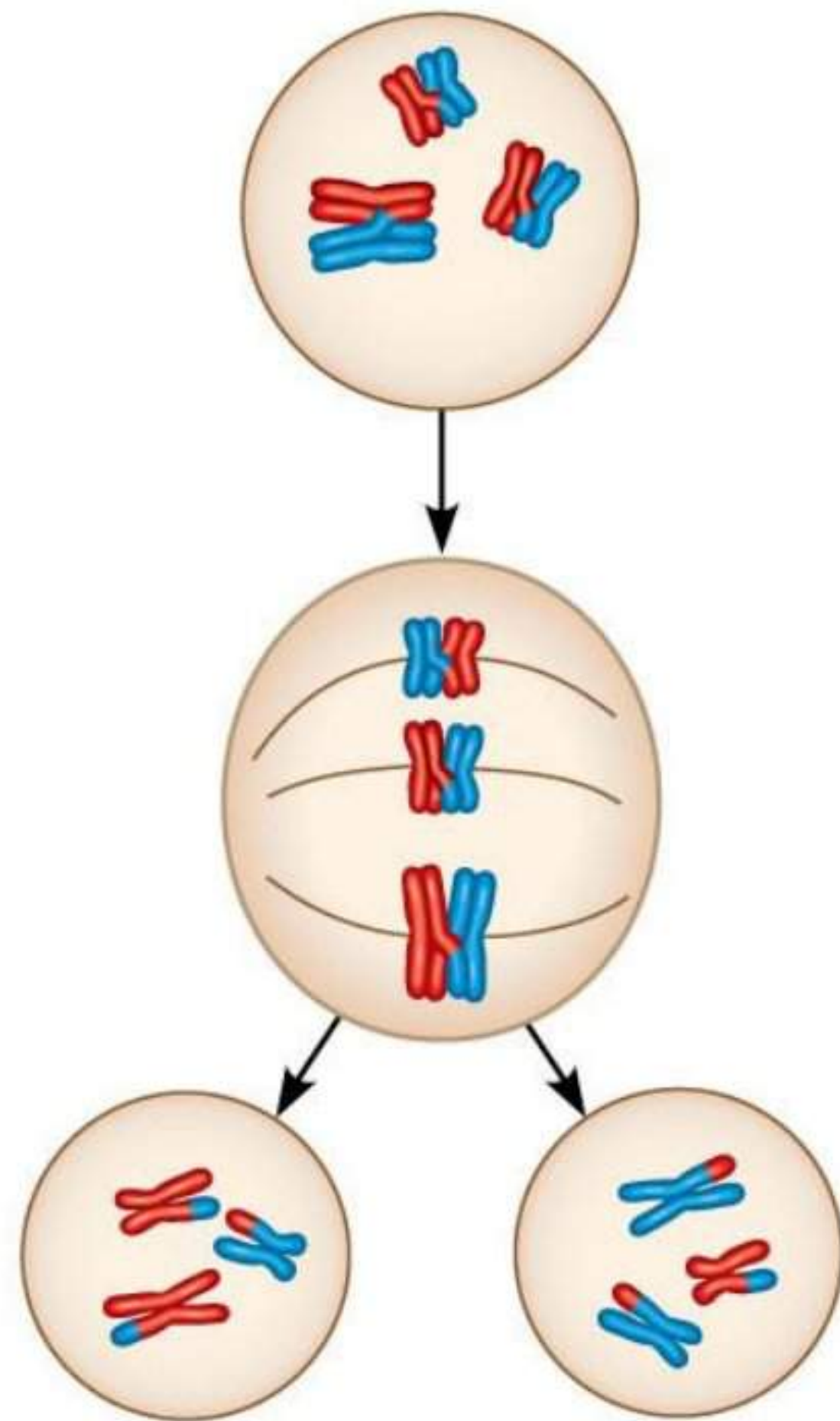
- Natural selection results in the accumulation of genetic variations favored by the environment
- Sexual reproduction contributes to the genetic variation in a population, which originates from mutations



Figure 13.12







**Prophase I: Each homologous pair 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.**



Figure 13.UN02

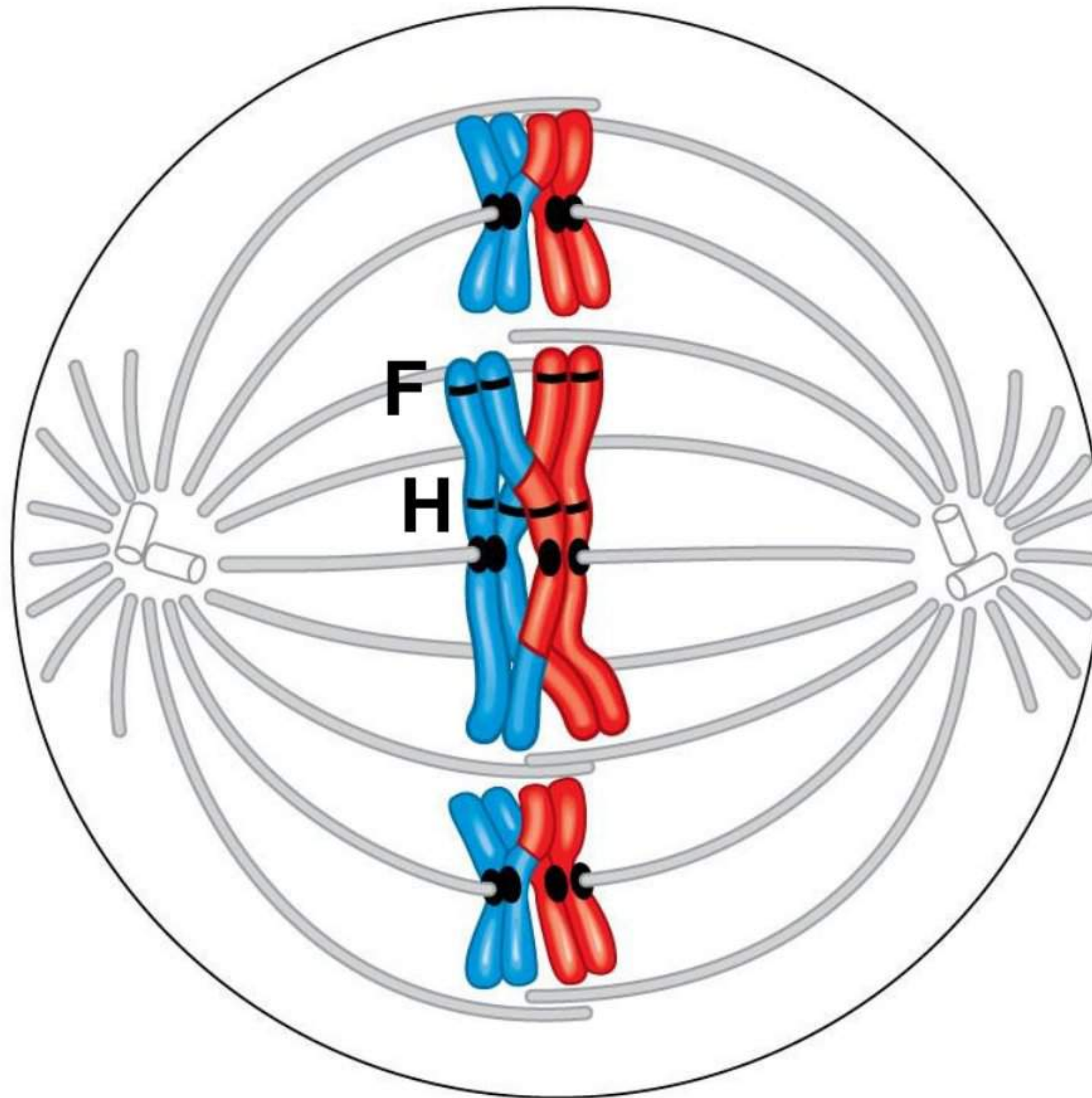




Figure 13.UN03

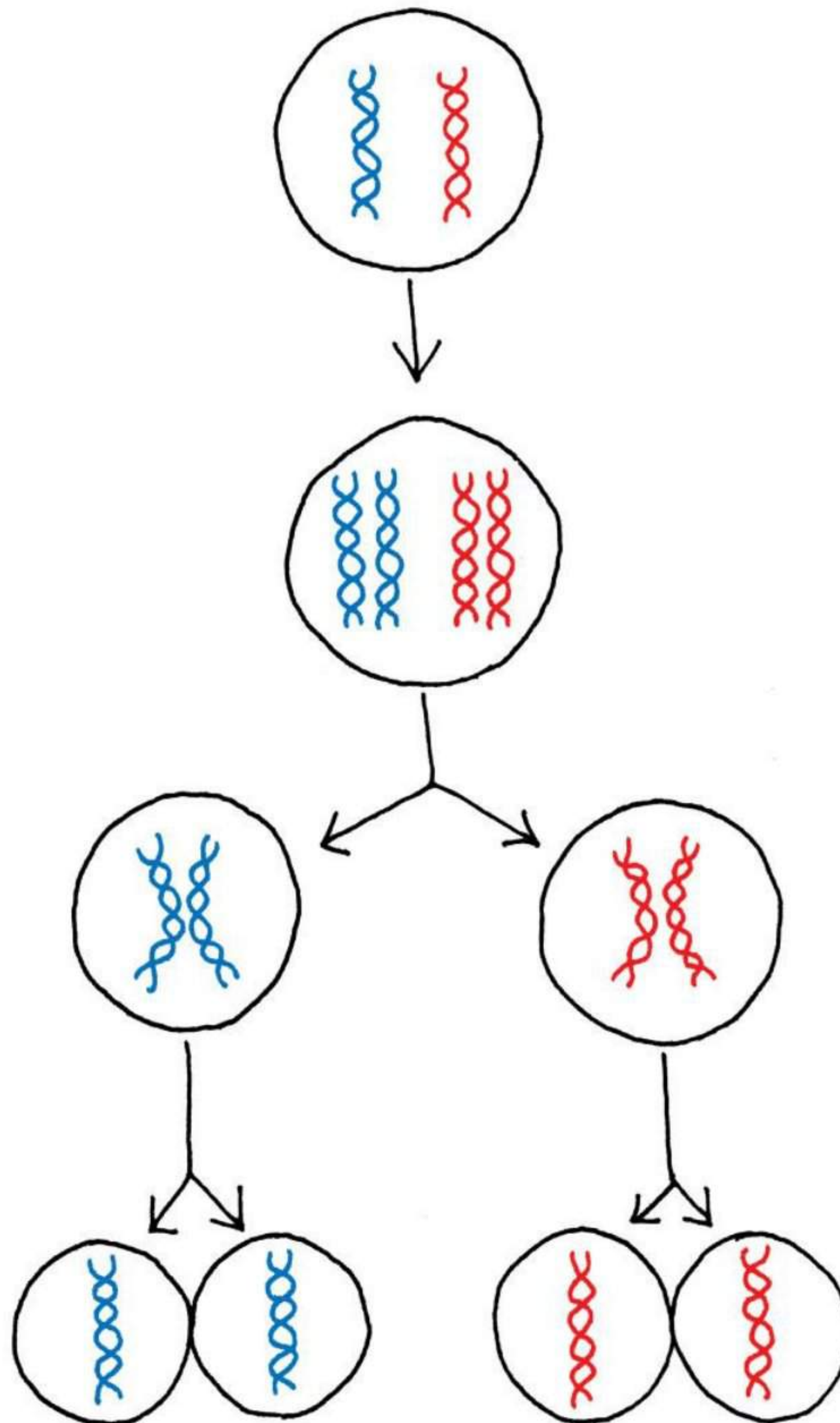
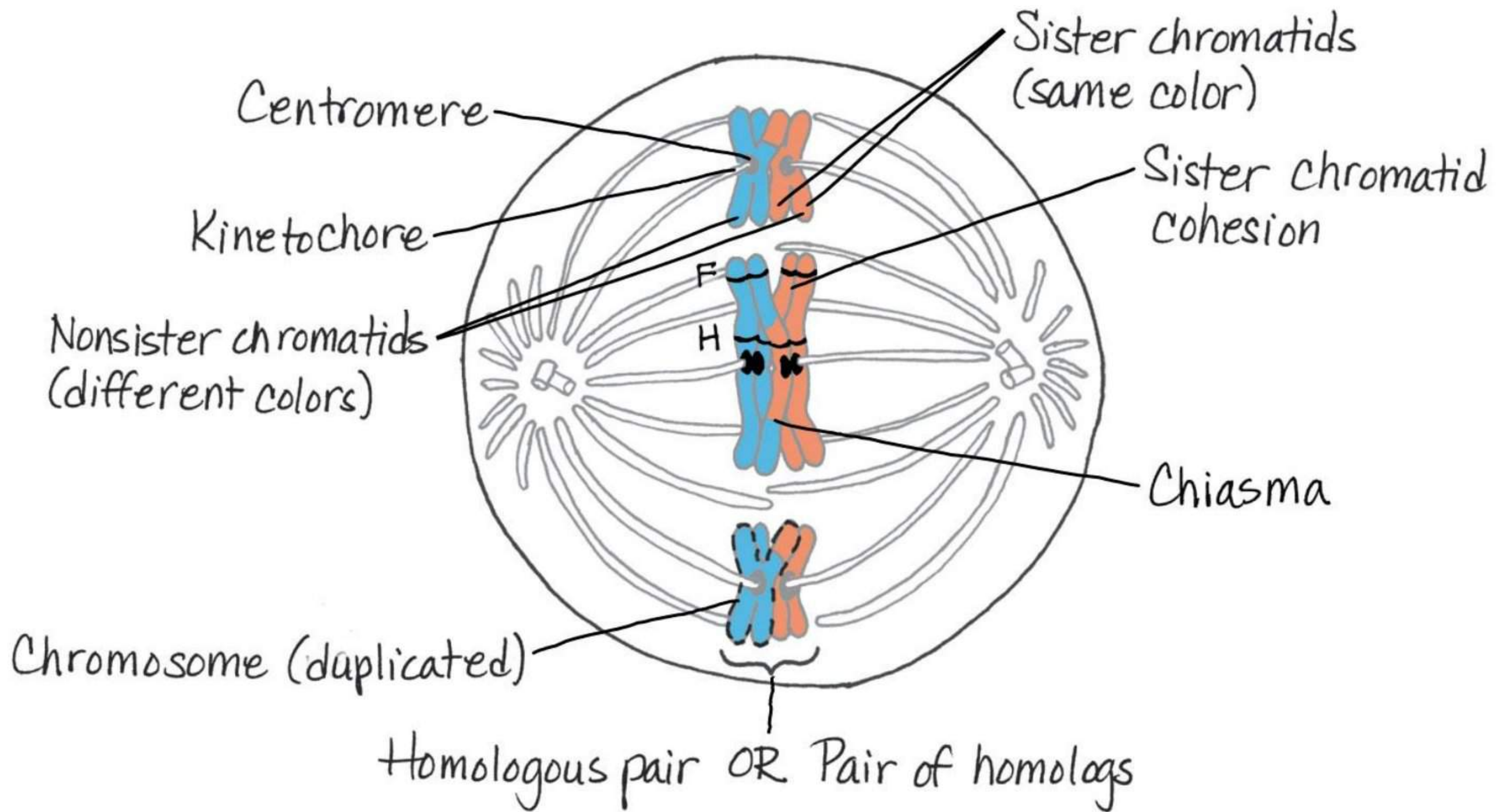




Figure 13.UN04



The chromosomes of one color make up a haploid set.  
All red and blue chromosomes together make up a diploid set.