Chapter 8

The Cellular Basis of Reproduction and Inheritance

PowerPoint Lectures for

Biology: Concepts & Connections, Sixth Edition
Campbell, Reece, Taylor, Simon, and Dickey

Lecture by Mary C. Colavito
Saving an endangered plant

- The bellflower is an endangered species in Hawaii
- When the last plant was flowering, rescuers bought pollen for sexual reproduction
- Unfortunately, no offspring were produced
- Asexual reproduction is now being attempted
CONNECTIONS BETWEEN CELL DIVISION AND REPRODUCTION
8.1 Like begets like, more or less

Living organisms reproduce by two methods

- **Asexual reproduction**
  - Offspring are identical to the original cell or organism
  - Involves inheritance of all genes from one parent

- **Sexual reproduction**
  - Offspring are similar to parents, but show variations in traits
  - Involves inheritance of unique sets of genes from two parents
8.2 Cells arise only from preexisting cells

- Cell division perpetuates life
  - Cell division is the reproduction of cells
  - Virchow’s principle states “Every cell from a cell”
8.2 Cells arise only from preexisting cells

- Roles of cell division
  - Asexual reproduction
    - Reproduction of an entire single-celled organism
    - Growth of a multicellular organism
    - Growth from a fertilized egg into an adult
    - Repair and replacement of cells in an adult
  - Sexual reproduction
    - Sperm and egg production
**Binary fission** means “dividing in half”

- Occurs in prokaryotic cells
- Two identical cells arise from one cell
- Steps in the process
  - A single circular chromosome duplicates, and the copies begin to separate from each other
  - The cell elongates, and the chromosomal copies separate further
  - The plasma membrane grows inward at the midpoint to divide the cells
Prokaryotic chromosome

1. Duplication of chromosome and separation of copies

Plasma membrane
Cell wall
Prokaryotic chromosome

1. Duplication of chromosome and separation of copies

2. Continued elongation of the cell and movement of copies
Prokaryotic chromosome

1. Duplication of chromosome and separation of copies

2. Continued elongation of the cell and movement of copies

3. Division into two daughter cells
Prokaryotic chromosomes
THE EUKARYOTIC CELL CYCLE AND MITOSIS
8.4 The large, complex chromosomes of eukaryotes duplicate with each cell division

- Eukaryotic chromosomes are composed of chromatin
  - Chromatin = DNA + proteins
  - To prepare for division, the chromatin becomes highly compact, and the chromosomes are visible with a microscope
  - Early in the division process, chromosomes duplicate
    - Each chromosome appears as two sister chromatids, containing identical DNA molecules
    - Sister chromatids are joined at the centromere, a narrow region
Sister chromatids

Centromere
Centromere

Chromosome duplication

Sister chromatids

Chromosome distribution to daughter cells
The cell cycle is an ordered sequence of events for cell division. It consists of two stages:

- **Interphase**: duplication of cell contents
  - \( G_1 \) — growth, increase in cytoplasm
  - \( S \) — duplication of chromosomes
  - \( G_2 \) — growth, preparation for division

- **Mitotic phase**: division
  - **Mitosis** — division of the nucleus
  - **Cytokinesis** — division of cytoplasm
8.6 Cell division is a continuum of dynamic changes

- Mitosis progresses through a series of stages
  - Prophase
  - Prometaphase
  - Metaphase
  - Anaphase
  - Telophase

- Cytokinesis often overlaps telophase
8.6 Cell division is a continuum of dynamic changes

- A **mitotic spindle** is required to divide the chromosomes
  - The mitotic spindle is composed of microtubules
  - It is produced by **centrosomes**, structures in the cytoplasm that
    - Organize microtubule arrangement
    - Contain a pair of centrioles in animal cells
      - The role of centrioles in cell division is unclear
INTERPHASE

- Centrosomes (with centriole pairs)
- Chromatin
- Nucleolus
- Nuclear envelope
- Plasma membrane

PROPHASE

- Early mitotic spindle
- Centrosome
- Chromosome, consisting of two sister chromatids

PROMETAPHASE

- Fragments of nuclear envelope
- Kinetochore
- Spindle microtubules
**INTERPHASE**
- Centrosomes (with centriole pairs)
- Chromatin
- Nuclear envelope
- Plasma membrane
- Nucleolus

**PROPHASE**
- Early mitotic spindle
- Centrosome
- Chromosome, consisting of two sister chromatids

**PROMETAPHASE**
- Fragments of nuclear envelope
- Kinetochore
- Spindle microtubules
PROPHASE
PROMETAPHASE
8.6 Cell division is a continuum of dynamic changes

- **Interphase**
  - In the cytoplasm
    - Cytoplasmic contents double
    - Two centrosomes form
  - In the nucleus
    - Chromosomes duplicate during the S phase
    - Nucleoli, sites of ribosome assembly, are visible
Applying Your Knowledge
Human cells have 46 chromosomes. By the end of interphase

– How many chromosomes are present in one cell?
– How many chromatids are present in one cell?
8.6 Cell division is a continuum of dynamic changes

- **Prophase**
  - In the cytoplasm
    - Microtubules begin to emerge from centrosomes, forming the spindle
  - In the nucleus
    - Chromosomes coil and become compact
    - Nucleoli disappear
8.6 Cell division is a continuum of dynamic changes

- **Prometaphase**
  - Spindle microtubules reach chromosomes, where they
    - Attach at kinetochores on the centromeres of sister chromatids
    - Move chromosomes to the center of the cell through associated protein “motors”
  - Other microtubules meet those from the opposite poles
  - The nuclear envelope disappears
METAPHASE

Metaphase plate

ANAPHASE

Daughter chromosomes

TELOPHASE AND CYTOKINESIS

Cleavage furrow

Nucleolus forming

Spindle

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METAPHASE

ANAPHASE

TELOPHASE AND CYTOKINESIS

Spindle

Metaphase plate

Daughter chromosomes

Cleavage furrow

Nucleolar forming

Nuclear envelope forming
METAPHASE
TELOPHASE AND CYTOKINESIS
Metaphase

- Spindle is fully formed
- Chromosomes align at the cell equator
- Kinetochore of sister chromatids are facing the opposite poles of the spindle

Applying Your Knowledge

By the end of metaphase

- How many chromosomes are present in one human cell?
- How many chromatids are present in one human cell?
Anaphase

- Sister chromatids separate at the centromeres
- Daughter chromosomes are moved to opposite poles of the cell
  - Motor proteins move the chromosomes along the spindle microtubules
  - Kinetochore microtubules shorten
- The cell elongates due to lengthening of nonkinetochore microtubules

Applying Your Knowledge
By the end of anaphase

- How many chromosomes are present in one human cell?
- How many chromatids are present in one human cell?
8.6 Cell division is a continuum of dynamic changes

- **Telophase**
  - The cell continues to elongate
  - The nuclear envelope forms around chromosomes at each pole, establishing daughter nuclei
  - Chromatin uncoils
  - Nucleoli reappear
  - The spindle disappears

- Applying Your Knowledge
  - By the end of telophase
    - How many chromosomes are present in one nucleus within the human cell?
    - Are the nuclei identical or different?

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8.6 Cell division is a continuum of dynamic changes

- **Cytokinesis**
  - Cytoplasm is divided into separate cells
  - Applying Your Knowledge
    By the end of cytokinesis
    - How many chromosomes are present in one human cell?
    - How many chromatids are present in one human cell?
Cytokinesis

- Cleavage in animal cells
  - A **cleavage furrow** forms from a contracting ring of microfilaments, interacting with myosin
  - The cleavage furrow deepens to separate the contents into two cells

- Cytokinesis in plant cells
  - A **cell plate** forms in the middle from vesicles containing cell wall material
  - The cell plate grows outward to reach the edges, dividing the contents into two cells
  - Each cell has a plasma membrane and cell wall
Cleavage furrow

Contracting ring of microfilaments

Daughter cells
Cleavage furrow

Contracting ring of microfilaments

Daughter cells
Cell plate

Wall of parent cell

Cell plate forming

Daughter nucleus

Daughter cells

New cell wall

Cell wall

Vesicles containing cell wall material

Cell plate

Daughter cells
- Wall of parent cell
- Cell plate forming
- Daughter nucleus
Cell wall

Vesicles containing cell wall material

New cell wall

Cell plate

Daughter cells
Factors that control cell division

- Presence of essential nutrients
- **Growth factors**, proteins that stimulate division
- Presence of other cells causes density-dependent inhibition
- Contact with a solid surface; most cells show anchorage dependence
Culture of cells

Addition of growth factor
Cells anchor to dish surface and divide.

When cells have formed a complete single layer, they stop dividing (density-dependent inhibition).

If some cells are scraped away, the remaining cells divide to fill the dish with a single layer and then stop (density-dependent inhibition).
Cell cycle control system

- A set of molecules, including growth factors, that triggers and coordinates events of the cell cycle

Checkpoints

- Control points where signals regulate the cell cycle
  - $G_1$ checkpoint allows entry into the $S$ phase or causes the cell to leave the cycle, entering a nondividing $G_0$ phase
  - $G_2$ checkpoint
  - M checkpoint
Control system

G₀ checkpoint

G₁ checkpoint

G₁

G₂ checkpoint

G₂

M checkpoint

S

M
8.9 Growth factors signal the cell cycle control system

- Effects of a growth factor at the G₁ checkpoint
  - A growth factor binds to a receptor in the plasma membrane
  - Within the cell, a signal transduction pathway propagates the signal through a series of relay molecules
  - The signal reaches the cell cycle control system to trigger entry into the S phase
Growth factor

Plasma membrane

Receptor protein

Signal transduction pathway

Relay proteins

G1 checkpoint

Control system

G1 S

M G2
8.10 CONNECTION: Growing out of control, cancer cells produce malignant tumors

- Cancer cells escape controls on the cell cycle
  - Cancer cells divide rapidly, often in the absence of growth factors
  - They spread to other tissues through the circulatory system
  - Growth is not inhibited by other cells, and tumors form
    - **Benign tumors** remain at the original site
    - **Malignant tumors** spread to other locations by metastasis
8.10 CONNECTION: Growing out of control, cancer cells produce malignant tumors

- Cancer treatments
  - Localized tumors can be treated with surgery or radiation
  - Chemotherapy is used for metastatic tumors
8.10 CONNECTION: Growing out of control, cancer cells produce malignant tumors

- Classification of cancer by origin
  - **Carcinomas** arise in external or internal body coverings
  - **Sarcomas** arise in supportive and connective tissue
  - **Leukemias** and **lymphomas** arise from blood-forming tissues
A tumor grows from a single cancer cell.

Cancer cells invade neighboring tissue.

Cancer cells spread through lymph and blood vessels to other parts of the body.
8.11 Review: Mitosis provides for growth, cell replacement, and asexual reproduction

- Mitosis produces genetically identical cells for
  - Growth
  - Replacement
  - Asexual reproduction
MEIOSIS AND CROSSING OVER
Somatic cells have pairs of homologous chromosomes, receiving one member of each pair from each parent.

Homologous chromosomes are matched in:
- Length
- Centromere position
- Gene locations
  - A locus (plural, loci) is the position of a gene
  - Different versions of a gene may be found at the same locus on maternal and paternal chromosomes.
8.12 Chromosomes are matched in homologous pairs

- The human **sex chromosomes** X and Y differ in size and genetic composition

- Pairs of **autosomes** have the same size and genetic composition

- Applying Your Knowledge

  - Humans have 46 chromosomes; how many homologous pairs does that represent?
  
  - If there is one pair of sex chromosomes, how many pairs of autosomes are found in humans?
Sister chromatids

Homologous pair of chromosomes

Centromere

One duplicated chromosome
Meiosis is a process that converts diploid nuclei to haploid nuclei.

- **Diploid cells** have two homologous sets of chromosomes.
- **Haploid cells** have one set of chromosomes.
- Meiosis occurs in the sex organs, producing **gametes**—sperm and eggs.

**Fertilization** is the union of sperm and egg.

- The **zygote** has a diploid chromosome number, one set from each parent.
Haploid gametes \((n = 23)\)

- Egg cell
- Sperm cell

Meiosis

Fertilization

Diploid zygote \((2n = 46)\)

Multicellular diploid adults \((2n = 46)\)

Mitosis and development
Like mitosis, **meiosis** is preceded by interphase

- Chromosomes duplicate during the S phase

Unlike mitosis, meiosis has two divisions

- During meiosis I, homologous chromosomes separate
  - The chromosome number is reduced by half
- During meiosis II, sister chromatids separate
  - The chromosome number remains the same

8.14 Meiosis reduces the chromosome number from diploid to haploid
8.14 Meiosis reduces the chromosome number from diploid to haploid

- Events in the nucleus during meiosis I
  - **Prophase I**
    - Chromosomes coil and become compact
    - Homologous chromosomes come together as pairs by synapsis
    - Each pair, with four chromatids, is called a tetrad
    - Nonsister chromatids exchange genetic material by crossing over
8.14 Meiosis reduces the chromosome number from diploid to haploid

- Applying Your Knowledge
  Human cells have 46 chromosomes. At the end of prophase I
    - How many chromosomes are present in one cell?
    - How many chromatids are present in one cell?
8.14 Meiosis reduces the chromosome number from diploid to haploid

- Events in the nucleus during meiosis I
  - **Metaphase I**
    - Tetrads align at the cell equator
  - **Anaphase I**
    - Homologous pairs separate and move toward opposite poles of the cell
- Applying Your Knowledge
  Human cells have 46 chromosomes. At the end of Metaphase I
  - How many chromosomes are present in one cell?
  - How many chromatids are present in one cell?
8.14 Meiosis reduces the chromosome number from diploid to haploid

- Events in the nucleus during meiosis I
  - Telophase I
    - Duplicated chromosomes have reached the poles
    - A nuclear envelope forms around chromosomes in some species
    - Each nucleus has the haploid number of chromosomes
  - Applying Your Knowledge
    After telophase I and cytokinesis
    - How many chromosomes are present in one human cell?
    - How many chromatids are present in one human cell?
**INTERPHASE**
- Centrosomes (with centriole pairs)
- Nuclear envelope
- Chromatin

**PROPHASE I**
- Sites of crossing over
- Spindle
- Chromatids
- Tetrad

**METAPHASE I**
- Microtubules attached to kinetochore
- Metaphase plate
- Centromere (with kinetochore)

**ANAPHASE I**
- Sister chromatids remain attached
- Homologous chromosomes separate

**MEIOSIS I: Homologous chromosomes separate**
Meiosis II follows meiosis I without chromosome duplication.

Each of the two haploid products enters meiosis II.

Events in the nucleus during meiosis II:

- Prophase II
  - Chromosomes coil and become compact.
8.14 Meiosis reduces the chromosome number from diploid to haploid

- Events in the nucleus during meiosis II
  - Metaphase II
    - Duplicated chromosomes align at the cell equator
  - Anaphase II
    - Sister chromatids separate and chromosomes move toward opposite poles
8.14 Meiosis reduces the chromosome number from diploid to haploid

- Events in the nucleus during meiosis II
  - Telophase II
    - Chromosomes have reached the poles of the cell
    - A nuclear envelope forms around each set of chromosomes
    - With cytokinesis, four haploid cells are produced
  - Applying Your Knowledge
    After telophase II and cytokinesis
    - How many chromosomes are present in one human cell?
    - How many chromatids are present in one human cell?
MEIOSIS II: Sister chromatids separate

TELOPHASE II AND CYTOKINESIS

PROPHASE I

METAPHASE II

ANAPHASE II

TELOPHASE II AND CYTOKINESIS

Cleavage furrow

Sister chromatids separate

Haploid daughter cells forming

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Which characteristics are similar for mitosis and meiosis?

- One duplication of chromosomes

Which characteristics are unique to meiosis?

- Two divisions of chromosomes
- Pairing of homologous chromosomes
- Exchange of genetic material by crossing over
What is the outcome of each process?

- Mitosis: two genetically identical cells, with the same chromosome number as the original cell
- Meiosis: four genetically different cells, with half the chromosome number of the original cell
**MITOSIS**

- **Prophase**
  - Duplicated chromosome (two sister chromatids)

- **Metaphase**
  - Chromosomes align at the metaphase plate

- **Anaphase**
  - Sister chromatids separate during anaphase

- **Telophase**
  - Daughter cells of mitosis

**MEIOSIS**

- **Prophase I**
  - Site of crossing over
  - Tetrads formed by synapsis of homologous chromosomes

- **Metaphase I**
  - Tetrads align at the metaphase plate

- **Anaphase I**
  - Homologous chromosomes separate (anaphase I); sister chromatids remain together

- **Telophase I**
  - Daughter cells of meiosis I

- **Anaphase II**
  - No further chromosomal duplication; sister chromatids separate (anaphase II)

- **Telophase II**
  - Daughter cells of meiosis II
Independent orientation at metaphase I
- Each pair of chromosomes independently aligns at the cell equator
- There is an equal probability of the maternal or paternal chromosome facing a given pole
- The number of combinations for chromosomes packaged into gametes is $2^n$ where $n = \text{haploid number of chromosomes}$

Random fertilization
- The combination of each unique sperm with each unique egg increases genetic variability
Two equally probable arrangements of chromosomes at metaphase I
Two equally probable arrangements of chromosomes at metaphase I

Possibility 1

Possibility 2

Metaphase II
Two equally probable arrangements of chromosomes at metaphase I

Possibility 1

Possibility 2

Combination 1

Combination 2

Combination 3

Combination 4

Gametes
Homologous chromosomes can carry different versions of genes

Separation of homologous chromosomes during meiosis can lead to genetic differences between gametes

- Homologous chromosomes may have different versions of a gene at the same locus

- One version was inherited from the maternal parent, and the other came from the paternal parent

- Since homologues move to opposite poles during anaphase I, gametes will receive either the maternal or paternal version of the gene
Brown coat ($C$); black eyes ($E$)

White coat ($c$); pink eyes ($e$)
Brown coat ($C$); black eyes ($E$)
White coat (c); pink eyes (e)
Coat-color genes

Brown

C

White

c

Eye-color genes

Black

E

Pink

c

Tetrad in parent cell (homologous pair of duplicated chromosomes)

Meiosis

Chromosomes of the four gametes
8.18 Crossing over further increases genetic variability

- Genetic recombination is the production of new combinations of genes due to crossing over.

- Crossing over involves exchange of genetic material between homologous chromosomes:
  - Nonsister chromatids join at a **chiasma** (plural, **chiasmata**), the site of attachment and crossing over.
  - Corresponding amounts of genetic material are exchanged between maternal and paternal (nonsister) chromatids.

Animation: Crossing Over
Breakage of homologous chromatids

Joining of homologous chromatids

Separation of homologous chromosomes at anaphase I

Separation of chromatids at anaphase II and completion of meiosis

Parental type of chromosome
Recombinant chromosome
Recombinant chromosome
Parental type of chromosome

Gametes of four genetic types
Breakage of homologous chromatids

Joining of homologous chromatids

Tetrad (homologous pair of chromosomes in synapsis)
Separation of homologous chromosomes at anaphase I

Separation of chromatids at anaphase II and completion of meiosis

Parental type of chromosome
Recombinant chromosome
Recombinant chromosome
Parental type of chromosome

Gametes of four genetic types
ALTERATIONS OF CHROMOSOME NUMBER AND STRUCTURE
A karyotype is a photographic inventory of an individual’s chromosomes

- A **karyotype** shows stained and magnified versions of chromosomes
  - Karyotypes are produced from dividing white blood cells, stopped at metaphase
  - Karyotypes allow observation of
    - Homologous chromosome pairs
    - Chromosome number
    - Chromosome structure
Packed red and white blood cells

Blood culture

Centrifuge

Fluid

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Packed red and white blood cells

Centrifuge Blood culture

Fluid

Hypotonic solution

1

2
Packed red and white blood cells

1. Blood culture

2. Hypotonic solution

3. Fixative

Fluid

Stain
Centromere

Sister chromatids

Pair of homologous chromosomes
Trisomy 21 involves the inheritance of three copies of chromosome 21

- Trisomy 21 is the most common human chromosome abnormality
- An imbalance in chromosome number causes **Down syndrome**, which is characterized by
  - Characteristic facial features
  - Susceptibility to disease
  - Shortened life span
  - Mental retardation
  - Variation in characteristics
- The incidence increases with the age of the mother
Infants with Down syndrome (per 1,000 births)

Age of mother

20 25 30 35 40 45 50

0 10 20 30 40 50 60 70 80 90

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8.21 Accidents during meiosis can alter chromosome number

- **Nondisjunction** is the failure of chromosomes or chromatids to separate during meiosis
  
  - During Meiosis I
    
    - Both members of a homologous pair go to one pole
  
  - During Meiosis II
    
    - Both sister chromatids go to one pole

- Fertilization after nondisjunction yields zygotes with altered numbers of chromosomes
Nondisjunction in meiosis I

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Nondisjunction in meiosis I

Normal meiosis II
Nondisjunction in meiosis I

Normal meiosis II

Gametes

Number of chromosomes

\( n + 1 \)  \( n + 1 \)  \( n - 1 \)  \( n - 1 \)
Normal meiosis I
Nondisjunction in meiosis II

Normal meiosis I
Nondisjunction in meiosis II

Gametes

Number of chromosomes

Normal meiosis I

Gamete number:

- \( n + 1 \)
- \( n - 1 \)
- \( n \)
- \( n \)
<table>
<thead>
<tr>
<th>Sex Chromosomes</th>
<th>Syndrome</th>
<th>Origin of Nondisjunction</th>
<th>Frequency in Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>XXY</td>
<td>Klinefelter syndrome (male)</td>
<td>Meiosis in egg or sperm formation</td>
<td>1/2,000</td>
</tr>
<tr>
<td>XYY</td>
<td>None (normal male)</td>
<td>Meiosis in sperm formation</td>
<td>1/2,000</td>
</tr>
<tr>
<td>XXX</td>
<td>None (normal female)</td>
<td>Meiosis in egg or sperm formation</td>
<td>1/1,000</td>
</tr>
<tr>
<td>XO</td>
<td>Turner syndrome (female)</td>
<td>Meiosis in egg or sperm formation</td>
<td>1/5,000</td>
</tr>
</tbody>
</table>

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Sex chromosome abnormalities tend to be less severe as a result of:

- Small size of the Y chromosome
- X-chromosome inactivation
  - In each cell of a human female, one of the two X chromosomes becomes tightly coiled and inactive
  - This is a random process that inactivates either the maternal or paternal chromosome
  - Inactivation promotes a balance between the number of X chromosomes and autosomes
Polyploid species have more than two chromosome sets

- Observed in many plant species
- Seen less frequently in animals

Example

- Diploid gametes are produced by failures in meiosis
- Diploid gamete + Diploid gamete → Tetraploid offspring
- The tetraploid offspring have four chromosome sets
Structure changes result from breakage and rejoining of chromosome segments

- **Deletion** is the loss of a chromosome segment
- **Duplication** is the repeat of a chromosome segment
- **Inversion** is the reversal of a chromosome segment
- **Translocation** is the attachment of a segment to a nonhomologous chromosome; can be reciprocal

Altered chromosomes carried by gametes cause birth defects

Chromosomal alterations in somatic cells can cause cancer
Deletion

Duplication

Homologous chromosomes

Inversion
Reciprocal translocation

Nonhomologous chromosomes
Chromosome 9

Activated cancer-causing gene

Chromosome 22

Reciprocal translocation

“Philadelphia chromosome”
Mitosis (division of nucleus) is genetically identical "daughter cells". INTERPHASE (cell growth and chromosome duplication) includes G1, S (DNA synthesis), and G2. Cytokinesis (division of cytoplasm) and Mitosis (division of nucleus) occur during the MITOTIC PHASE (M).
Haploid gametes ($n = 23$)

Egg cell

Sperm cell

Meiosis

Fertilization

Multicellular diploid adults ($2n = 46$)

Diploid zygote ($2n = 46$)

Mitosis and development
<table>
<thead>
<tr>
<th></th>
<th>Mitosis</th>
<th>Meiosis</th>
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<tbody>
<tr>
<td>Number of chromosomal duplications</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of cell divisions</td>
<td></td>
<td></td>
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<tr>
<td>Number of daughter cells produced</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of chromosomes in daughter cells</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How chromosomes line up during metaphase</td>
<td></td>
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<tr>
<td>Genetic relationship of daughter cells to parent cell</td>
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<td></td>
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<tr>
<td>Functions performed in the human body</td>
<td></td>
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</tbody>
</table>
You should now be able to

1. Identify the roles of cell division in living organisms
2. Distinguish between events in interphase, mitosis, and cytokinesis
3. Describe the movements of chromosomes in prophase, metaphase, anaphase, and telophase of mitosis
4. Define the following terms: checkpoint, chiasma, chromosome, chromatid, centromere, crossing over, homologous chromosome pair, nondisjunction, and spindle
5. Compare and contrast the processes of mitosis and meiosis

6. Distinguish between terms in the following groups: haploid—diploid; sister chromatids—nonsister chromatids; deletion—duplication—inversion—translocation

7. Describe how genetic variability is generated through meiosis and fertilization

8. Identify factors that control cell division and describe how cancer cells escape these controls