Lecture Series 5

Cell Cycle & Cell Division
Reading Assignments

• Read Chapter 18
  Cell Cycle & Cell Division
• Read Chapter 19
  pages 651-663 only
  (Benefits of Sex & Meiosis sections - these are in Chapter 20 in 2nd Edition)
A. Systems of Cell Division

• Cell division is necessary for reproduction, growth, and repair of an organism.
• Cell division must be initiated by three steps: DNA replication, DNA separation, and then division of the cytoplasm.
• In microbes, cellular DNA is a single molecule, or chromosome. Bacteria & Archaea reproduce by binary fission.
• In eucaryotes, nuclei divide by either mitosis or meiosis.
Bacterial cell division (binary fission):

1. Chromosome replication begins. Soon thereafter, one copy of the origin begins to move toward the other end of the cell.

2. Replication continues. One copy of the origin is now at each end of the cell.

3. Replication finishes. The plasma membrane grows inward, and new cell wall is deposited.

4. Two daughter cells result.
Universal functions of the cell cycle

- Replicate the DNA.
- Segregate it into daughter cells.
- Replicate and/or distribute organelles into daughter cells.
- Grow & do it again!
B. Interphase and the Control of Cell Division

- The mitotic cell cycle has two main phases: interphase and mitosis.
- Interphase is the period between divisions in the cytoplasm.
- During most of the cell cycle the cell is in interphase, which is divided into three subphases: S, G1, and G2.
- DNA is replicated during S phase.
The mitotic cell cycle

- **G₁ PHASE**
- **S PHASE** (DNA replication)
- **G₂ PHASE**
- **INTERPHASE**
- **M PHASE** (mitosis (nuclear division) and cytokinesis (cytoplasmic division))
FACS analysis
(flourescence-activated cell sorting)
B. Interphase and the Control of Cell Division

- Cyclin-Cdk complexes regulate the passage of cells from G1 into S phase and from G2 into M phase, etc.
- Cyclin binding to Cdk exposes the active site of the protein kinase but breaks down quickly.
- These complexes act as checkpoints regulating the cells progression through the cell cycle.
G1 into S phase:
Cyclin dependant kinases

1. Association with cyclins.

2. Activating phosphorylation of threonine around position 160.

3. Inhibitory phosphorylation of threonine 14 and tyrosine 15.

4. Association with Cdk inhibitors (CKI's).
Cyclin dependant kinases bind to different cyclins
Processes regulated by Cyclin dependant kinases

- **G1**: Cell Growth
- **S**: DNA Synthesis
- **G2**: Spindle Formation
- **M**: Chromosome Condensation
Activity is regulated by Cyclin degradation

Targeted destruction in Proteosomes
B. Interphase and the Control of Cell Division

- In addition to the internal cyclin-Cdk complexes, **external** controls to the cell, such as growth factors and hormones, can also stimulate a division cycle.
- **Cancer cells** often have defective Cyclin-Cdk complexes or lose external control over their growth factors.
Density-dependent inhibition of cell division

(a) Normal mammalian cells

Cells anchor to dish surface and divide (anchorage dependence).

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 gap and then stop (density-dependent inhibition).

(b) Cancer cells

Cancer cells do not exhibit anchorage dependence or density-dependent inhibition.
C. Eucaryotic Chromosomes

- Chromosomes contain DNA and proteins. At mitosis, chromosomes initially appear double because two sister chromatids are held together at the centromere.
- Each sister chromatid consists of one double-stranded DNA molecule complexed with proteins and referred to as chromatin.
What essential process happens in S phase? DNA Replication!
Chromosome duplication and distribution during mitosis
C. Eucaryotic Chromosomes

- During interphase, DNA in chromatin is wound around histone core proteins to form nucleosomes.
- DNA folds repeatedly, packing within the nucleus. When mitotic chromosomes form, it supercoils and condenses even more.
Nucleosomes aka “beads on a string”

2 meter long molecule into 5 \( \mu \text{m} \) nucleus!
Cohesins and condensins help prepare replicated chromosomes for mitosis.
D. Mitosis: Distributing Exact Copies of Genetic Information

- After DNA is replicated during S phase, the first sign of mitosis is the duplication of the centrosome, which initiates microtubule formation for the spindle.
- Rem: dynamic instability.
The centrosome duplicates to form the two poles of a mitotic spindle.
Each pair of sister chromatids separates to become two daughter chromosomes.
D. Mitosis: Distributing Exact Copies of Genetic Information

- Mitosis is continuous, but can be divided into 5 stages: prophase, prometaphase, metaphase, anaphase, and telophase.
- Cytokinesis occurs in the 6th stage, overlapping with the end of mitosis.
**Mitotic cell division stages (animal cell): prophase; prometaphase.**

<table>
<thead>
<tr>
<th>G₂ OF INTERPHASE</th>
<th>PROPHASE</th>
<th>PROMETAPHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centrosomes</td>
<td>Early mitotic spindle</td>
<td>Fragments of nuclear envelope</td>
</tr>
<tr>
<td>(with centriole pairs)</td>
<td>Chromatin spindle</td>
<td>Kinetochore</td>
</tr>
<tr>
<td>Aster</td>
<td>Centromere</td>
<td>Nonkinetochore microtubules</td>
</tr>
<tr>
<td>Chromatin (duplicated)</td>
<td>Spindle pole</td>
<td>Kinetochores</td>
</tr>
<tr>
<td>Nucleolus</td>
<td>Chromosome, consisting of two sister chromatids</td>
<td></td>
</tr>
<tr>
<td>Nuclear envelope</td>
<td>Plasma membrane</td>
<td></td>
</tr>
</tbody>
</table>

**Images:**
- [Prophase](image1)
- [Prometaphase](image2)
- [Animal cell](image3)
Mitotic cell division stages (animal cell): metaphase; anaphase; telophase.
D. Mitosis: Distributing Exact Copies of Genetic Information

- During prophase, the chromosomes condense and appear as paired chromatids.
- During prometaphase, the chromosomes move toward the middle of the spindle. The nuclear envelope breaks down. Kinetochore microtubules appear and attach the kinetochores to the centrosomes.
The centromere region of a chromosome
Three classes of microtubules make up the mitotic spindle.
D. Mitosis: Distributing Exact Copies of Genetic Information

- In metaphase, chromatids gather at the middle of the cell, their centromeres on the metaphase plate.
- In anaphase, the centromeres holding the chromatid pairs together separate. Each member of the pair, now called a daughter chromosome, migrates to its pole along the microtubule track.
The mitotic spindle at metaphase

(a) Diagram of two duplicated chromosomes arrayed at the metaphase plate

(b) Transmission electron micrographs

Anaphase Promoting Complex (APC)
Anaphase Promoting Complex (APC)

(a) The anaphase-promoting complex targets securin and mitotic cyclin for degradation. It destroys securin allows separase to cleave the cohesins that hold sister chromatids together, thereby initiating anaphase.

1. The destruction of mitotic cyclin depresses mitotic Cdk activity, leading to cytokinesis, chromosome decondensation, and nuclear envelope reassembly.
What drives the movements at anaphase?

**Anaphase A**
Chromosomes are pulled poleward.

- Shortening of kinetochore microtubules: forces are generated at kinetochores to move chromosomes toward their spindle pole.

**Anaphase B**
Poles are pushed and pulled apart.

- A sliding force (1) is generated between interpolar microtubules from opposite poles to push the poles apart; a pulling force (2) acts directly on the poles to move them apart.

- Microtubule growth at plus end of interpolar microtubules.
D. Mitosis: Distributing Exact Copies of Genetic Information

- During telophase, the chromosomes become less condensed. The nuclear envelopes and nucleoli re-form, producing two nuclei whose chromosomes are identical to each other and to those of the cell that began the cycle.
Nuclear envelope reassembly
Mitosis in a plant cell (sans centrosome)
E. Cytokinesis: The Division of the Cytoplasm

- Cytokinesis usually follows nuclear division. Animal cell cytoplasm usually divides by plasma membrane furrowing caused by contraction of cytoplasmic actin filaments.
- In plant cells, cytokinesis is accomplished by vesicle fusion and the synthesis of new cell wall material by phragmoplast.
Cytokinesis in animal and plant cells

(a) Cleavage of an animal cell (SEM)

(b) Cell plate formation in a plant cell (TEM)
Cytokinesis in plant cells is guided by microtubule-based phragmoplast.
Mitosis in an onion root
A hypothesis for the evolution of mitosis

<table>
<thead>
<tr>
<th>Hypothetical sequence</th>
<th>Evidence from modern organisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacterial chromosome</td>
<td>(a) Prokaryotes</td>
</tr>
<tr>
<td>Chromosomes</td>
<td>(b) Dinoflagellates</td>
</tr>
<tr>
<td>Microtubules</td>
<td></td>
</tr>
<tr>
<td>Intact nuclear envelope</td>
<td>(c) Diatoms</td>
</tr>
<tr>
<td>Kinetochore microtubules</td>
<td>(d) Most eukaryotes</td>
</tr>
<tr>
<td>Intact nuclear envelope</td>
<td></td>
</tr>
<tr>
<td>Centrosome</td>
<td></td>
</tr>
<tr>
<td>Fragments of nuclear envelope</td>
<td></td>
</tr>
</tbody>
</table>
E. Cytokinesis: The Division of the Cytoplasm

- The cell cycle can repeat itself many times, forming a clone of genetically identical cells.
- Asexual reproduction produces an organism genetically identical to the parent. Any genetic variety is the result of mutations.
F. Meiosis: Sexual Reproduction and Diversity

• In sexual reproduction, two haploid gametes—one from each parent—unite in fertilization to form a genetically unique, diploid zygote.
• The number shape and size of metaphase chromosomes constitute a karyotype.
• The more chromosome pairs there are in a diploid cell, the greater the diversity of chromosome combinations generated by meiosis.
• Humans have 23 pairs of chromosomes.
Chromosome Painting and respective Karyotype
Three sexual life cycles differing in the timing of meiosis and fertilization (syngamy)

- **Animals**
  - Meiosis → Fertilization
  - Diploid multicellular organism → Mitosis
  - Zygote → 2n

- **Most fungi and some algae**
  - Meiosis → Fertilization
  - Haploid multicellular organism → Mitosis
  - Gametes → n
  - Zygote → 2n

- **Plants and some algae**
  - Meiosis → Fertilization
  - Haploid multicellular organism (gametophyte) → Mitosis
  - Spores → n
  - Gametes → n
  - Zygote → 2n

- **Alternation of generations**
The human life cycle

- Random Fertilization
F. Meiosis: Sexual Reproduction and Diversity

- In sexually reproducing organisms, certain cells in the adult undergo meiosis, whereby a diploid cell produces haploid gametes.
- Each gamete contains a random mix of one of each pair of homologous chromosomes from the parent.
- Zygotes are formed by random fertilization which increases diversity.
G. Meiosis: A Pair of Nuclear Divisions

• Meiosis reduces the chromosome number from diploid to haploid and ensures that each haploid cell contains one member of each chromosome pair. It consists of two nuclear divisions.

• We often refer to meiosis as **reduction-division**.
Overview of meiosis: how meiosis reduces chromosome number

Interphase 1 of Meiosis
- Homologous pair of chromosomes in diploid parent cell
- Chromosomes replicate
- Homologous pair of replicated chromosomes
- Sister chromatids
- Diploid cell with replicated chromosomes

Meiosis I
1. Homologous chromosomes separate
2. Haploid cells with replicated chromosomes

Meiosis II
2. Sister chromatids separate
3. Haploid cells with unreplicated chromosomes
The stages of meiotic cell division: Meiosis I

**MEIOSIS I:** Separates homologous chromosomes

<table>
<thead>
<tr>
<th>INTERPHASE</th>
<th>PROPHASE I</th>
<th>METAPHASE I</th>
<th>ANAPHASE I</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Centrosomes (with centriole pairs)</strong></td>
<td><strong>Chiasmata</strong></td>
<td><strong>Microtubule attached to kinetochore</strong></td>
<td><strong>Sister chromatids remain attached</strong></td>
</tr>
<tr>
<td><strong>Nuclear envelope</strong></td>
<td><strong>Spindle</strong></td>
<td><strong>Metaphase plate</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Chromatin</strong></td>
<td><strong>Sister chromatids</strong></td>
<td><strong>Centromere (with kinetochore)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Chromosomes duplicate</strong></td>
<td><strong>Homologous chromosomes pair and exchange segments</strong></td>
<td><strong>Tetrads line up</strong></td>
<td><strong>Pairs of homologous chromosomes split up</strong></td>
</tr>
</tbody>
</table>
The stages of meiotic cell division: Meiosis II

**MEIOSIS II:** Separates sister chromatids

**TELOPHASE I AND CYTOKINESIS**

Cleavage furrow

Two haploid cells form; chromosomes are still double

During another round of cell division, the sister chromatids finally separate; four haploid daughter cells result, containing single chromosomes

Sister chromatids separate

Haploid daughter cells forming
G. Meiosis: A Pair of Nuclear Divisions

- During prophase I of the first meiotic division, homologous chromosomes pair, and material may be exchanged by crossing over between nonsister chromatids of two adjacent homologs.

- In metaphase I, the paired homologs gather at the equatorial plate. Each chromosome has one kinetochore and associates with polar microtubules for one pole.

- In anaphase I, entire chromosomes, each with two chromatids, migrate to the poles. By the end of meiosis I, there are two nuclei, each with the haploid number of chromosomes but with two sister chromatids.
Synapsis: Crossing over of nonsister chromatids.
The results of crossing over during meiosis

- Crossing over increases diversity.
The results of alternative arrangements of two homologous chromosome pairs on the metaphase plate in meiosis I aka Independent Assortment.

- Independent Assortment increases diversity.

**Possibility 1**

Two equally probable arrangements of chromosomes at metaphase I

- Combination 1
- Combination 2

**Possibility 2**

- Combination 3
- Combination 4
G. Meiosis: A Pair of Nuclear Divisions

- In meiosis II, the sister chromatids separate. No DNA replication precedes this division, which in other aspects is similar to mitosis. The result of meiosis is four cells, each with a haploid chromosome content.
Mitosis is a mechanism for constancy: The parent nucleus produces two daughter nuclei, identical to the parent and to each other.
Meiosis is a mechanism for diversity: The parent nucleus produces four haploid daughter nuclei, each different from the parent and from its sisters.
H. Origins of Genetic Variation Among Offspring

- **Mutations**
  - Are the original source of genetic variation.
- **Sexual Reproduction**
  - Produces new combinations of variant genes, adding more genetic diversity.
H. Origins of Genetic Variation Among Offspring

- In species that produce sexually, the behavior of chromosomes during meiosis AND fertilization is responsible for most of the variation that arises each generation. Genetics = Applied Meiosis!

- **Independent Assortment of Chromosomes**
  - Homologous pairs of chromosomes orient randomly at metaphase I of meiosis.

- **Crossing over**
  - Produces recombinant chromosomes that carry genes derived from two different parents during prophase I of meiosis.

- **Random Fertilization**
  - The fusion of gametes will produce a zygote with any of about 64 trillion diploid combinations.
Combos: $2^n$ where $n = \# \text{ chromosome pairs}$
I. Meiotic Errors: Source of Chromosomal Disorders

- In **nondisjunction**, one member of a homologous pair of chromosomes fails to separate from the other, and both go to the same pole. This event leads to one gamete with an extra chromosome and another other lacking that chromosome.

- Fertilization with a normal haploid gamete results in **aneuploidy** and genetic abnormalities that are invariably harmful or lethal to the organism.
Nondisjunction in gamete

Aneuploidy in zygote
J. Cell Death

- Cells may die by necrosis or may self-destruct by apoptosis, a genetically programmed series of events that includes the detachment of the cell from its neighbors and the fragmentation of its nuclear DNA.
### 9.2 Two Different Ways for Cells to Die

<table>
<thead>
<tr>
<th></th>
<th>NECROSIS</th>
<th>APOPTOSIS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stimuli</strong></td>
<td>Low $O_2$, toxins, ATP depletion, damage</td>
<td>Specific, genetically programmed physiological signals</td>
</tr>
<tr>
<td><strong>ATP required</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Cellular pattern</strong></td>
<td>Swelling, organelle disruption, tissue death</td>
<td>Chromatin condensation, membrane blebbing, single-cell death</td>
</tr>
<tr>
<td><strong>DNA breakdown</strong></td>
<td>Random fragments</td>
<td>Nucleosome-sized fragments</td>
</tr>
<tr>
<td><strong>Plasma membrane</strong></td>
<td>Burst</td>
<td>Blebbed</td>
</tr>
<tr>
<td><strong>Fate of dead cells</strong></td>
<td>Ingested by phagocytes</td>
<td>Ingested by neighboring cells</td>
</tr>
<tr>
<td><strong>Reaction in tissue</strong></td>
<td>Inflammation</td>
<td>No inflammation</td>
</tr>
</tbody>
</table>
Membrane “Blebbing” by a WBC via apoptosis.