Chapter 3

The Cellular Level of Organization

An Introduction to Cells

- Cell Theory
  - Developed from Robert Hooke's research
    - Cells are the building blocks of all plants and animals
    - All cells come from the division of preexisting cells
    - Cells are the smallest units that perform all vital physiological functions
    - Each cell maintains homeostasis at the cellular level

An Introduction to Cells

- **Sex Cells** (*Germ Cells*)
  - Reproductive cells
  - Male sperm
  - Female *oocyte* (a cell that develops into an egg)
- Somatic Cells
  - *Soma* = body
  - All body cells except sex cells

3-1 Plasma Membrane

- Extracellular Fluid (Interstitial Fluid)
  - A watery medium that surrounds a cell
  - **Plasma membrane** (**cell membrane**) separates cytoplasm from the extracellular fluid
  - Cytoplasm
    - Cytosol = liquid
    - Intracellular structures collectively known as organelles

3-1 Plasma Membrane

- Functions of the Plasma Membrane
  - *Physical Isolation*
    - Barrier
  - *Regulation of Exchange with the Environment*
    - Ions and nutrients enter
    - Wastes eliminated and cellular products released

3-1 Plasma Membrane

- Functions of the Plasma Membrane
  - *Sensitivity to the Environment*

        - Extracellular fluid composition
        - Chemical signals
    - *Structural Support*
        - Anchors cells and tissues

3-1 Plasma Membrane

- Membrane Lipids
    - **Phospholipid bilayer**
        - Hydrophilic heads — toward watery environment, both sides
        - Hydrophobic fatty-acid tails — inside membrane
        - Barrier to ions and water — soluble compounds

3-1 Plasma Membrane

- Membrane Proteins
    - **Integral proteins**
        - Within the membrane
    - **Peripheral proteins**
        - Bound to inner or outer surface of the membrane

3-1 Plasma Membrane

- Membrane Proteins
    - **Anchoring proteins** (stabilizers)
        - Attach to inside or outside structures
    - Recognition proteins (*identifiers*)
        - Label cells as normal or abnormal
    - *Enzymes*
        - Catalyze reactions

3-1 Plasma Membrane

- Membrane Proteins
    - **Receptor proteins**
        - Bind and respond to **ligands** (ions, hormones)
    - **Carrier proteins**
        - Transport specific solutes through membrane
    - **Channels**
        - Regulate water flow and solutes through membrane

3-1 Plasma Membrane

- Membrane Carbohydrates
    - *Proteoglycans*, *glycoproteins*, and *glycolipids*
        - Extend outside cell membrane
        - Form sticky “sugar coat” (**glycocalyx**)

- Functions of the glycocalyx
  - *Lubrication* and Protection
  - *Anchoring* and *Locomotion*
  - *Specificity* in Binding (receptors)
  - *Recognition* (immune response)

3-2 Organelles and the Cytoplasm

- **Cytoplasm**
  - All materials inside the cell and outside the nucleus
    - **Cytosol** (*intracellular* fluid)
      - Dissolved materials
        - Nutrients, ions, proteins, and waste products
      - High potassium/low sodium
      - High protein
      - High carbohydrate/low amino acid and fat
    - **Organelles**
      - Structures with specific functions

3-2 Organelles and the Cytoplasm

- The Organelles
  - **Nonmembranous** organelles
    - No membrane
    - Direct contact with cytosol
    - Include the *cytoskeleton*, microvilli, centrioles, *cilia*, *ribosomes*, and *proteasomes*
  - **Membranous organelles**
    - Covered with plasma membrane
    - Isolated from cytosol
    - Include the *endoplasmic reticulum* (*ER*), *the Golgi apparatus*, *lysosomes*, *peroxisomes*, and *mitochondria*

3-2 Organelles and the Cytoplasm

- **Nonmembranous Organelles**
  - Six types of nonmembranous organelles
    1. Cytoskeleton
    2. Microvilli
    3. Centrioles
    4. Cilia
    5. Ribosomes
    6. Proteasomes

3-2 Organelles and the Cytoplasm

- The **Cytoskeleton**

- Structural proteins for shape and strength
  - **Microfilaments**
  - **Intermediate filaments**
  - **Microtubules**

3-2 Organelles and the Cytoplasm

- The Cytoskeleton
  - **Microfilaments** — thin filaments composed of the protein **actin**
    - Provide additional mechanical strength
    - Interact with proteins for consistency
    - Pair with thick filaments of *myosin* for muscle movement

3-2 Organelles and the Cytoplasm

- The Cytoskeleton
  - **Intermediate filaments** — mid-sized between microfilaments and thick filaments
    - Durable (**collagen**)
    - Strengthen cell and maintain shape
    - Stabilize organelles
    - Stabilize cell position

3-2 Organelles and the Cytoplasm

- The Cytoskeleton
  - **Microtubules** — large, hollow tubes of **tubulin** protein
    - Attach to centrosome
    - Strengthen cell and anchor *organelles*
    - Change cell shape
    - Move vesicles within cell (*kinesin* and *dynein*)
    - Form spindle apparatus

3-2 Organelles and the Cytoplasm

- The Cytoskeleton
  - **Thick filaments**
    - **Myosin** protein in muscle cells

3-2 Organelles and the Cytoplasm

- **Microvilli**
  - Increase surface area for absorption
  - Attach to cytoskeleton
- **Centrioles** in the **Centrosome**
  - Centrioles form spindle apparatus during cell division
  - Centrosome: cytoplasm surrounding centriole

- **Cilia**
  - Small hairlike extensions
    - Cilia move fluids across the cell surface

3-2 Organelles and the Cytoplasm

- Ribosomes
  - Build polypeptides in protein synthesis
  - Two types
    1. **Free ribosomes** in cytoplasm
       - Manufacture proteins for cell
    2. **Fixed ribosomes** attached to *ER*
       - Manufacture proteins for secretion
- **Proteasomes**
  - Contain enzymes (*proteases*)
  - Disassemble damaged proteins for recycling

3-2 Organelles and the Cytoplasm

- Membranous Organelles
  - Five types of membranous organelles
    1. **Endoplasmic reticulum (ER)**
    2. **Golgi apparatus**
    3. **Lysosomes**
    4. **Peroxisomes**
    5. **Mitochondria**

3-2 Organelles and the Cytoplasm

- Endoplasmic Reticulum (ER)
  - *Endo-* = within, *plasm* = cytoplasm, *reticulum* = network
  - **Cisternae** are storage chambers within membranes
  - Functions
    1. *Synthesis* of proteins, carbohydrates, and lipids
    2. *Storage* of synthesized molecules and materials
    3. *Transport* of materials within the ER
    4. *Detoxification* of drugs or toxins

3-2 Organelles and the Cytoplasm

- **Endoplasmic Reticulum** (**ER**)
  - *Smooth endoplasmic reticulum* (*SER*)
    - No ribosomes attached
    - Synthesizes lipids and carbohydrates
      - Phospholipids and cholesterol (membranes)
      - Steroid hormones (reproductive system)

- Glycerides (storage in liver and fat cells)
- Glycogen (storage in muscles)

3-2 Organelles and the Cytoplasm

- **Endoplasmic Reticulum** (**ER**)
  - *Rough endoplasmic reticulum* (*RER*)
    - Surface covered with ribosomes
      - Active in protein and glycoprotein synthesis
      - Folds polypeptide protein structures
      - Encloses products in **transport vesicles**

3-2 Organelles and the Cytoplasm

- **Golgi Apparatus**
  - Vesicles enter forming face and exit maturing face
  - Functions
    1. Modifies and packages secretions
       - Hormones or enzymes
       - Released through exocytosis
    2. Renews or modifies the plasma membrane
    3. Packages special enzymes within vesicles for use in the cytoplasm

3-2 Organelles and the Cytoplasm

- **Lysosomes**
  - Powerful enzyme-containing vesicles
    - *Lyso-* = dissolve, *soma* = body
  - *Primary lysosome*
    - Formed by Golgi apparatus and inactive enzymes
  - *Secondary lysosome*
    - Lysosome fused with damaged organelle
    - Digestive enzymes activated
    - Toxic chemicals isolated

3-2 Organelles and the Cytoplasm

- Lysosomes
  - Functions
    1. Clean up inside cells
    2. **Autolysis**

3-2 Organelles and the Cytoplasm

- Clean Up Inside Cells
  - Break down large molecules
  - Attack bacteria

- Recycle damaged organelles
- Eject wastes by exocytosis

3-2 Organelles and the Cytoplasm

- **Autolysis**
  - *Auto-* = self, *lysis* = break
  - Self-destruction of damaged cells
    - Lysosome membranes break down
    - Digestive enzymes released
    - Cell decomposes
    - Cellular materials recycle

3-2 Organelles and the Cytoplasm

- **Peroxisomes**
  - Are enzyme-containing vesicles
    - Break down fatty acids, organic compounds
    - Produce hydrogen peroxide (H_2O_2)
    - Replicate by division

3-2 Organelles and the Cytoplasm

- **Membrane Flow**
  - A continuous exchange of membrane parts by vesicles
    - All membranous organelles (except mitochondria)
    - Allows adaptation and change

3-2 Organelles and the Cytoplasm

- **Mitochondria**
  - Have smooth outer membrane and inner membrane with numerous folds (**cristae**)
  - **Matrix**
    - Fluid around cristae
  - *Mitochondrion* takes chemical energy from food (glucose)
    - Produces energy molecule ATP

3-2 Organelles and the Cytoplasm

- Mitochondrial Energy Production
  - **Glycolysis**
    - Glucose to pyruvic acid (in cytosol)
  - Citric acid cycle (also known as the *Krebs cycle* and the *tricarboxylic acid cycle*, or *TCA cycle*)
    - Pyruvic acid to CO_2 (in matrix)
  - Electron transport chain

        - Inner mitochondrial membrane

3-2 Organelles and the Cytoplasm

- Mitochondrial Energy Production
    - Called **aerobic metabolism** (cellular respiration)
        - Mitochondria use oxygen to break down food and produce ATP
        - Glucose + oxygen + ADP → carbon dioxide + water + ATP

3-3 Cell Nucleus

- **Nucleus**
    - Largest organelle
    - The cell's control center
    - **Nuclear envelope**
        - Double membrane around the nucleus
    - **Perinuclear space**
        - Between the two layers of the nuclear envelope
    - **Nuclear pores**
        - Communication passages

3-3 Cell Nucleus

- Contents of the Nucleus
    - DNA
        - All information to build and run organisms
    - *Nucleoplasm*
        - Fluid containing ions, enzymes, nucleotides, and some RNA
    - **Nuclear matrix**
        - Support filaments

3-3 Cell Nucleus

- Contents of the Nucleus
    - **Nucleoli**
        - Are related to protein production
        - Are made of RNA, enzymes, and **histones**
        - Synthesize rRNA and ribosomal subunits
    - **Nucleosomes**
        - DNA coiled around histones

3-3 Cell Nucleus

- Contents of the Nucleus
    - **Chromatin**
        - Loosely coiled DNA (cells not dividing)
    - **Chromosomes**

        - Tightly coiled DNA (cells dividing)

3-3 Cell Nucleus

- Information Storage in the Nucleus
    - DNA
        - Instructions for every protein in the body
    - **Gene**
        - DNA instructions for one protein
    - **Genetic code**
        - The chemical language of DNA instructions
            - Sequence of bases (A, T, C, G)
        - Triplet code
            - 3 bases = 1 amino acid

3-4 Protein Synthesis

- The Role of Gene Activation in Protein Synthesis
    - The nucleus contains chromosomes
    - Chromosomes contain DNA
    - DNA stores genetic instructions for proteins
    - Proteins determine cell structure and function

3-4 Protein Synthesis

- The Role of Gene Activation in Protein Synthesis
    - **Gene activation** — uncoiling DNA to use it
        - Promoter
        - Terminator
    - **Transcription**
        - Copies instructions from DNA to mRNA (in nucleus)
        - **RNA polymerase** produces **messenger RNA** (**mRNA**)

3-4 Protein Synthesis

- The Role of Gene Activation in Protein Synthesis
    - Translation
        - Ribosome reads code from mRNA (in cytoplasm)
        - Assembles amino acids into polypeptide chain
    - Processing
        - RER and Golgi apparatus produce protein

3-4 Protein Synthesis

- The Transcription of mRNA
    - A gene is *transcribed* to mRNA in three steps
        1. **Gene activation**

2. **DNA to mRNA**
3. **RNA processing**

3-4 Protein Synthesis

- **Step 1: Gene activation**
  - Uncoils DNA, removes histones
  - Start (promoter) and stop codes on DNA mark location of gene
    - **Coding strand** is code for protein
    - **Template strand** is used by RNA polymerase molecule

3-4 Protein Synthesis

- **Step 2: DNA to mRNA**
  - Enzyme RNA polymerase transcribes DNA
    - Binds to promoter (*start*) sequence
    - Reads DNA code for gene
    - Binds nucleotides to form messenger RNA (mRNA)
    - mRNA duplicates DNA coding strand, uracil replaces thymine

3-4 Protein Synthesis

- **Step 3: RNA processing**
  - At *stop* signal, mRNA detaches from DNA molecule
    - Code is edited (**RNA processing**)
    - Unnecessary codes (**introns**) removed
    - Good codes (**exons**) spliced together
    - Triplet of three nucleotides (**codon**) represents one amino acid

3-4 Protein Synthesis

- **Translation**
  - mRNA moves:
    - From the nucleus through a nuclear pore
  - mRNA moves:
    - To a ribosome in cytoplasm surrounded by amino acids
  - mRNA binds to ribosomal subunits
    - tRNA delivers amino acids to mRNA

3-4 Protein Synthesis

- **Translation**
  - tRNA **anticodon** binds to mRNA codon
    - One mRNA codon *translates* to one amino acid
  - Enzymes join amino acids with peptide bonds
    - Polypeptide chain has specific *sequence* of amino acids
  - At *stop codon*, components separate

3-4 Protein Synthesis

- How the Nucleus Controls Cell Structure and Function
    1. *Direct* control through synthesis of:
        - Structural proteins
        - Secretions (environmental response)
    2. *Indirect* control over metabolism through enzymes

3-5 Diffusion and Osmosis

- Membrane Transport
    - The plasma (cell) membrane is a barrier, but:
        - Nutrients must get in
        - Products and wastes must get out
    - **Permeability** determines what moves in and out of a cell, and a membrane that:
        - Lets nothing in or out is **impermeable**
        - Lets anything pass is **freely permeable**
        - Restricts movement is **selectively permeable**

3-5 Diffusion and Osmosis

- Membrane Transport
    - Plasma membrane is **selectively permeable**
        - Allows some materials to move freely
        - Restricts other materials
    - Selective permeability restricts materials based on:
        - Size
        - Electrical charge
        - Molecular shape
        - Lipid solubility

3-5 Diffusion and Osmosis

- Membrane Transport
    - Transport through a plasma membrane can be:
        - *Active* (requiring energy and ATP)
        - *Passive* (no energy required)
    - Diffusion (passive)
    - Carrier-mediated transport (passive or active)
    - Vesicular transport (active)

3-5 Diffusion and Osmosis

- Diffusion
    - All molecules are constantly in motion
    - Molecules in solution move randomly

- Random motion causes mixing
- Concentration is the amount of solute in a solvent
- **Concentration gradient**
  - More solute in one part of a solvent than another

3-5 Diffusion and Osmosis

- Factors Influencing Diffusion
  - *Distance* the particle has to move
  - *Molecule Size*
    - Smaller is faster
  - *Temperature*
    - More heat, faster motion
  - *Concentration gradient*
    - The difference between high and low concentrations
  - *Electrical forces*
    - Opposites attract, like charges repel

3-5 Diffusion and Osmosis

- Diffusion across Plasma Membranes
  - Can be simple or channel mediated
    - Materials that diffuse through plasma membrane by **simple diffusion**
      - Lipid-soluble compounds (alcohols, fatty acids, and steroids)
      - Dissolved gases (oxygen and carbon dioxide)

3-5 Diffusion and Osmosis

- Diffusion across Plasma Membranes
  - *Channel-mediated diffusion*
    - Water-soluble compounds and ions
  - Factors in channel-mediated diffusion
    - Size
    - Charge
    - Interaction with the channel — **leak channels**

3-5 Diffusion and Osmosis

- Osmosis: A Special Case of Diffusion
  - **Osmosis** is the diffusion of water across the cell membrane
    - More solute molecules, lower concentration of water molecules
    - Membrane must be freely permeable to water, selectively permeable to solutes
    - Water molecules diffuse across membrane toward solution with more solutes
    - Volume increases on the side with more solutes

3-5 Diffusion and Osmosis

- Osmosis: A Special Case of Diffusion
  - *Osmotic pressure*
    - Is the force of a concentration gradient of water
    - Equals the force (**hydrostatic pressure**) needed to block osmosis

3-5 Diffusion and Osmosis

- Osmolarity and Tonicity
  - The osmotic effect of a solute on a cell
    - Two fluids may have equal **osmolarity**, but different **tonicity**
  - **Isotonic** (*iso-* = same, *tonos* = tension)
    - A solution that does not cause osmotic flow of water in or out of a cell
  - **Hypotonic** (*hypo-* = below)
    - Has less solutes and loses water through osmosis
  - **Hypertonic** (*hyper-* = above)
    - Has more solutes and gains water by osmosis

3-5 Diffusion and Osmosis

- Osmolarity and Tonicity
  - A cell in a hypotonic solution:
    - Gains water
    - Ruptures (**hemolysis** of red blood cells)
  - A cell in a hypertonic solution:
    - Loses water
    - Shrinks (**crenation** of red blood cells)

3-6 Carriers and Vesicles

- **Carrier-Mediated Transport**
  - Of ions and organic substrates
    - Characteristics
      - *Specificity*
        - One transport protein, one set of substrates
      - *Saturation limits*
        - Rate depends on transport proteins, not substrate
      - *Regulation*
        - Cofactors such as hormones

3-6 Carriers and Vesicles

- Carrier-Mediated Transport
  - **Cotransport**
    - Two substances move in the same direction at the same time
  - **Countertransport**

        - One substance moves in while another moves out

3-6 Carriers and Vesicles

- Carrier-Mediated Transport
    - **Facilitated diffusion**
        - Passive
        - Carrier proteins transport molecules too large to fit through channel proteins (glucose, amino acids)
            - Molecule binds to **receptor site** on carrier protein
            - Protein changes shape, molecules pass through
            - Receptor site is specific to certain molecules

3-6 Carriers and Vesicles

- Carrier-Mediated Transport
    - Active transport (primary or secondary)
        - Active transport proteins
            - Move substrates against concentration gradient
    - Require energy, such as ATP
            - **Ion pumps** move ions (Na^+, K^+, Ca^{2+}, Mg^{2+})
            - **Exchange pump** countertransports two ions at the same time

3-6 Carriers and Vesicles

- Carrier-Mediated Transport
    - Primary active transport
        - **Sodium–potassium exchange pump**
            - Active transport, carrier mediated
            - Sodium ions (Na^+) out, potassium ions (K^+) in
            - 1 ATP moves 3 Na^+ and 2 K^+

3-6 Carriers and Vesicles

- Carrier-**Mediated Transport**
    - **Secondary active transport**
        - Na^+ concentration gradient drives glucose transport
        - ATP energy pumps Na^+ back out

3-6 Carriers and Vesicles

- **Vesicular Transport** (*Bulk Transport*)
    - Materials move into or out of cell in **vesicles**
        - **Endocytosis** (*endo-* = inside) is active transport using ATP
            - *Receptor mediated*
            - *Pinocytosis*
            - *Phagocytosis*

3-6 Carriers and Vesicles

- Endocytosis
  - **Receptor-mediated endocytosis**
    - Receptors (glycoproteins) bind target molecules (**ligands**)
    - **Coated vesicle** (endosome) carries ligands and receptors into the cell

3-6 Carriers and Vesicles

- Endocytosis
  - **Pinocytosis**
    - Endosomes “drink” extracellular fluid
  - **Phagocytosis**
    - **Pseudopodia** (*pseudo-* = false, *pod-* = foot)
    - Engulf large objects in **phagosomes**
- **Exocytosis** (*exo-* = outside)
  - Granules or droplets are released from the cell

3-7 Transmembrane Potential

- Transmembrane Potential
  - Charges are separated creating a **potential difference**
  - Unequal charge across the plasma membrane is **transmembrane potential**
  - **Resting potential** ranges from –10 mV to –100 mV, depending on cell type

3-8 Cell Life Cycle

- Cell Life Cycle
  - Most of a cell’s life is spent in a nondividing state (interphase)
  - Body (somatic) cells divide in three stages
    - **DNA replication** duplicates genetic material exactly
    - **Mitosis** divides genetic material equally
    - Cytokinesis divides cytoplasm and organelles into two **daughter cells**

3-8 Cell Life Cycle

- DNA Replication
  - *Helicases* unwind the DNA strands
  - DNA polymerase
    1. Promotes bonding between the nitrogenous bases of the DNA strand and complementary DNA nucleotides dissolved in the nucleoplasm
    2. Links the nucleotides by covalent bonds
  - DNA polymerase works in one direction
  - **Ligases** piece together sections of DNA

3-8 Cell Life Cycle

- **Interphase**
  - The nondividing period
    - **G-zero (G_0) phase** — specialized cell functions only
    - **G_1 phase** — cell growth, organelle duplication, protein synthesis
    - **S phase** — DNA replication and histone synthesis
    - **G_2 phase** — finishes protein synthesis and centriole replication

3-8 Cell Life Cycle

- **Mitosis**
  - Divides duplicated DNA into two sets of **chromosomes**
    - DNA coils tightly into **chromatids**
    - Chromatids connect at a **centromere**
    - Protein complex around centromere is **kinetochore**

3-8 Cell Life Cycle

- Mitosis
  - **Prophase**
    - Nucleoli disappear
    - Centriole pairs move to cell poles
    - Microtubules (**spindle fibers**) extend between centriole pairs
    - Nuclear envelope disappears
    - Spindle fibers attach to **kinetochore**
  - **Metaphase**
    - Chromosomes align in a central plane (metaphase plate)

3-8 Cell Life Cycle

- Mitosis
  - **Anaphase**
    - Microtubules pull chromosomes apart
    - **Daughter chromosomes** group near centrioles
  - **Telophase**
    - Nuclear membranes re-form
    - Chromosomes uncoil
    - Nucleoli reappear
    - Cell has two complete nuclei

3-8 Cell Life Cycle

- **Cytokinesis**
  - Division of the cytoplasm
    - Cleavage furrow around metaphase plate
    - Membrane closes, producing daughter cells

3-8 Cell Life Cycle

- The Mitotic Rate and Energy Use
  - Rate of cell division
    - Slower **mitotic rate** means longer cell life
    - Cell division requires energy (ATP)
  - Muscle cells, neurons rarely divide
  - Exposed cells (skin and digestive tract) live only days or hours — replenished by **stem cells**

3-9 Regulation of the Cell Life Cycle

- Cell Division
  - Normally, cell division balances cell loss
  - Increased cell division
    - Internal factors (**M-phase promoting factor**, **MPF**)
    - Extracellular chemical factors (**growth factors**)
  - Decreased cell division
    - *Repressor genes* (faulty repressors cause cancers)
    - Worn out **telomeres** (terminal DNA segments)

3-10 Cell Division and Cancer

- Cancer Develops in Steps
  - Abnormal cell
  - Primary tumor
  - Metastasis
  - Secondary tumor

3-10 Cell Division and Cancer

- **Tumor** (*Neoplasm*)
  - Enlarged mass of cells
  - Abnormal cell growth and division
  - *Benign tumor*
    - Contained, not life threatening unless large
  - *Malignant tumor*
    - Spreads into surrounding tissues (**invasion**)
    - Starts new tumors (**metastasis**)

3-11 Differentiation

- Differentiation
  - All cells carry complete DNA instructions for all body functions
  - Cells specialize or **differentiate**
    - To form tissues (liver cells, fat cells, and neurons)
    - By turning *off* all genes not needed by that cell

- All body cells, except sex cells, contain the same 46 chromosomes
- Differentiation depends on which genes are active and which are inactive