Complete Biology

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Contents

Overview. This complete note provides an undergraduate-level review of biology, from the molecular chemistry of life and cellular structure through genetics, evolution, organismal physiology, ecology, and experimental methods. Each section integrates essential vocabulary, key mechanisms, quantitative tools, and canonical experiments. The progression mirrors the logical structure of the discipline: chemistry → cell → genetics → evolution → diversity → organism → ecology. Use this overview to identify gaps and navigate directly to the topics you need to review.

1 Unifying Principles of Life: Cells, Information, Energy, and Evolution

1.1 Core ideas

All living organisms share a set of unifying properties: they are composed of cells, process hereditary information encoded in DNA, extract and use energy from their environment, and evolve through natural selection.

The **cell theory** states that (1) all living things are composed of one or more cells, (2) the cell is the basic structural and functional unit of life, and (3) all cells arise from pre-existing cells. Cells are classified as **prokaryotic** (lacking a membrane-bound nucleus; bacteria and archaea) or **eukaryotic** (possessing a nucleus and membrane-bound organelles; protists, fungi, plants, animals). Despite their differences, all cells share a plasma membrane, cytoplasm, ribosomes, and a DNA genome.

The **central dogma of molecular biology** (Crick, 1958) describes the flow of genetic information: DNA $\rightarrow$ RNA $\rightarrow$ Protein. DNA stores information; transcription produces messenger RNA (mRNA); translation uses mRNA to assemble polypeptides. This information is heritable and subject to mutation, providing the raw material for evolution.

Life requires a constant input of energy. **Metabolism** encompasses all chemical reactions in an organism. **Catabolism** breaks down molecules to release energy; **anabolism** uses energy to build molecules. The universal energy currency is **ATP** (adenosine triphosphate). The **first law of thermodynamics** (energy conservation) and the **second law** (entropy increases) govern all biological processes. Living systems maintain **homeostasis** – internal stability – by expending energy to oppose entropy.

Evolution by natural selection is the central organizing principle of biology. Darwin and Wallace (1858) proposed that individuals with heritable traits better suited to their environment survive and reproduce more successfully, causing populations to change over generations. The four postulates are: (1) variation exists among individuals, (2) variation is heritable, (3) more offspring are produced than can survive, (4) survival and reproduction are non-random.

For review, be able to: list the properties of life; state the cell theory; explain the central dogma; define metabolism, catabolism, anabolism, and ATP; interpret the two laws of thermodynamics in biological context; describe natural selection's four postulates; distinguish prokaryotes from eukaryotes; explain why entropy makes energy input necessary.

Section summary Life is defined by cells, genetic information, energy harvesting, and evolution. The cell theory, central dogma, metabolism, thermodynamics, and natural selection form the conceptual foundation. All biological complexity rests on these five pillars.

2 The Chemistry of Life: Water, Carbon, and Macromolecules

2.1 Core ideas

Life is carbon-based and operates in an aqueous medium. **Water** is polar, forms hydrogen bonds, and has emergent properties: high specific heat, high heat of vaporization, cohesion, adhesion, and expansion upon freezing. These properties arise from extensive hydrogen bonding between water molecules. Water is the universal solvent in biology, dissolving polar and ionic compounds (hydrophilic) while excluding non-polar ones (hydrophobic).

Carbon forms four covalent bonds, allowing an immense diversity of organic molecules. **Functional groups** (hydroxyl, carbonyl, carboxyl, amino, sulfhydryl, phosphate, methyl) confer distinct chemical properties. **Isomers** (structural, geometric, enantiomers) add further complexity. Enantiomers are mirror-image molecules; biological systems typically use only one form (e.g., L-amino acids, D-sugars).

The four major classes of **macromolecules** are carbohydrates, lipids, proteins, and nucleic acids. All are polymers assembled from monomers via **dehydration synthesis** (condensation) and broken down by **hydrolysis**.

- **Carbohydrates:** Composed of monosaccharides ($C_nH_{2n}O_n$). Glucose ($C_6H_{12}O_6$) is the central energy source. Disaccharides (sucrose, lactose) form via glycosidic linkages. Polysaccharides (starch, glycogen, cellulose, chitin) serve storage or structural roles. Cellulose, a $\beta(1 \to 4)$ polymer of glucose, is indigestible by most animals but essential as dietary fiber.
- **Lipids:** Hydrophobic molecules including fats (triacylglycerols), phospholipids, and steroids. Fats store energy (~ 37 kJ/g, twice that of carbohydrates). Phospholipids form bilayers – the basis of all membranes. Steroids (e.g., cholesterol, testosterone) have a four-ring carbon skeleton.
- **Proteins:** Polymers of amino acids joined by peptide bonds. There are 20 standard amino acids with varied side chains (non-polar, polar uncharged, charged). Protein structure has four levels: primary (amino acid sequence), secondary (α-helices and β-sheets stabilized by hydrogen bonds), tertiary (overall 3D folding), and quaternary (multi-subunit assembly). Function is determined by structure; denaturation (unfolding) destroys function.
- **Nucleic acids:** DNA and RNA are polymers of nucleotides. Each nucleotide has a phosphate, a pentose sugar (deoxyribose in DNA, ribose in RNA), and a nitrogenous base (A, G, C, T in DNA; A, G, C, U in RNA). DNA is double-stranded with antiparallel strands held by complementary base pairing (A–T, G–C). RNA is typically single-stranded.

For review, be able to: explain water's emergent properties; identify functional groups; name the four macromolecule classes; describe polymerization by dehydration synthesis; distinguish α and β glucose linkages; explain the four levels of protein structure; draw a nucleotide; state Chargaff's rules (base pairing).

Section summary Water's hydrogen-bonding chemistry makes it the ideal biological solvent. Carbon's tetravalency enables the rich diversity of organic molecules. Four macromolecule classes – carbohydrates, lipids, proteins, and nucleic acids – are built from monomers and serve as structural, energetic, informational, and catalytic components of life.

3 The Cell: Membranes, Organelles, Metabolism, and Signaling

3.1 Core ideas

The **plasma membrane** is a phospholipid bilayer with embedded proteins. The **fluid mosaic model** (Singer and Nicolson, 1972) describes membranes as dynamic structures where lipids and proteins diffuse laterally. Membrane proteins function as transporters, enzymes, receptors, and anchors.

Transport across membranes occurs by **passive transport** (diffusion, facilitated diffusion via channel or carrier proteins) requiring no energy, and **active transport** (pumps, endocytosis, exocytosis) requiring ATP. **Osmosis** is the diffusion of water across a selectively permeable membrane. Tonicity (hypertonic, hypotonic, isotonic) describes the effect on cell volume.

Organelles compartmentalize eukaryotic cells:

- **Nucleus:** Contains DNA; enclosed by a double membrane (nuclear envelope) with nuclear pores. The nucleolus produces ribosomal RNA.
- **Ribosomes:** Sites of protein synthesis (free in cytoplasm or bound to rough ER).

- **Endoplasmic reticulum (ER):** Rough ER (studded with ribosomes) processes secretory proteins; smooth ER synthesizes lipids and detoxifies.
- **Golgi apparatus:** Modifies, sorts, and packages proteins for transport.
- **Lysosomes:** Contain hydrolytic enzymes for intracellular digestion (autophagy, phagocytosis).
- **Mitochondria:** Sites of cellular respiration; contain their own DNA and double membranes. The inner membrane folds into cristae to increase surface area.
- **Chloroplasts (plants):** Sites of photosynthesis; contain thylakoid membranes stacked into grana.
- **Peroxisomes:** Break down fatty acids and detoxify hydrogen peroxide.
- **Cytoskeleton:** Network of microfilaments (actin), intermediate filaments, and microtubules (tubulin) providing structure, motility, and intracellular transport.

Cell signaling involves reception (ligand binds receptor), transduction (signal relay via phosphorylation cascades, second messengers like cAMP, Ca^{2+}, IP_3), and response (gene expression, metabolism change). Major receptor types: G protein-coupled receptors (GPCRs), receptor tyrosine kinases (RTKs), and ion channel receptors.

For review, be able to: describe the fluid mosaic model; compare passive and active transport; explain osmosis and tonicity; list organelle functions; outline the endomembrane system; trace a signal from receptor to response; distinguish paracrine, synaptic, and endocrine signaling.

Section summary The plasma membrane controls exchange between cell and environment. Eukaryotic organelles compartmentalize functions from energy production to protein trafficking. Cell signaling networks allow cells to sense and respond to their surroundings. The endosymbiotic theory explains the origins of mitochondria and chloroplasts.

4 Genetic Information: DNA, RNA, and Proteins

4.1 Core ideas

DNA replication is semiconservative (Meselson and Stahl, 1958). Each parental strand serves as a template for a new complementary strand. Key enzymes: helicase (unwinds), DNA polymerase III (synthesizes new strand $5' \to 3'$), primase (lays RNA primers), ligase (seals Okazaki fragments on the lagging strand). The leading strand is synthesized continuously; the lagging strand discontinuously.

Transcription produces RNA from a DNA template. RNA polymerase (bacterial: one type; eukaryotic: RNA Pol I, II, III) binds the promoter region and synthesizes RNA $5' \to 3'$. In eukaryotes, pre-mRNA undergoes processing: $5'$ cap addition, $3'$ poly-A tail, and **splicing** (introns removed, exons joined). Alternative splicing generates multiple proteins from one gene.

Translation occurs on ribosomes. mRNA codons (three-nucleotide sequences) specify amino acids via the **genetic code**. The code is degenerate (64 codons, 20 amino acids + stop codons), nearly universal, and read from a start codon (AUG, methionine). tRNA molecules carry anticodons and deliver amino acids. Ribosomes have three sites: A (aminoacyl), P (peptidyl), E (exit). Peptide bond formation is catalyzed by the ribozyme activity of rRNA. Elongation continues until a stop codon (UAA, UAG, UGA) is reached; release factors trigger disassembly.

Gene regulation controls when and how much protein is produced. Prokaryotes use **operons** (e.g., lac operon: repressor, inducer, promoter, operator, structural genes). Eukaryotic regulation is more complex: transcription factors, enhancers, silencers, chromatin remodeling, histone modifications (acetylation activates; methylation can activate or repress), and **epigenetics** (heritable changes not due to DNA sequence, e.g., DNA methylation patterns).

Key experimental evidence: Griffith (1928) discovered transformation; Avery, MacLeod, McCarty (1944) identified DNA as the transforming principle; Hershey and Chase (1952) confirmed DNA as phage genetic material using radioactive isotopes (^{35}S labeled protein, ^{32}P labeled DNA).

For review, be able to: diagram replication fork; explain semiconservative replication; describe RNA processing; use the genetic code table; explain how ribosomes translate mRNA; contrast prokaryotic and eukaryotic gene regulation; define operon, promoter, enhancer, spliceosome, ribozyme, epigenetic mark.

Section summary Genetic information flows from DNA to RNA to protein. DNA replicates semiconservatively and is transcribed into RNA, which is translated into protein according to the universal genetic code. Regulation of gene expression occurs at multiple levels, from chromatin structure to mRNA stability. The operon model in prokaryotes and epigenetic mechanisms in eukaryotes exemplify this control.

5 Genetics and Genomes: From Mendel to CRISPR

5.1 Core ideas

Mendelian genetics rests on the work of Gregor Mendel (1865) on pea plants. Key principles:

- **Law of Segregation:** Each individual has two alleles for each gene; they segregate during gamete formation.
- **Law of Independent Assortment:** Genes on different chromosomes assort independently during meiosis.

Mendel's monohybrid crosses yielded 3:1 phenotypic ratios in the F_2 generation. A **Punnett square** predicts offspring genotypes. Dominance relationships: complete, incomplete (pink snapdragons from red $\times$ white), and codominance (ABO blood type).

Extensions to Mendel: Pleiotropy (one gene affects multiple traits, e.g., Marfan syndrome). **Epistasis** (one gene masks another, e.g., coat color in Labrador retrievers). **Polygenic inheritance** (multiple genes affect one trait, e.g., human height, skin color). **Linkage** (genes on the same chromosome do not assort independently). Recombination frequency maps gene distance: 1 map unit = 1% recombination.

Sex determination varies: XY system (mammals), ZW system (birds), XO system (some insects), haplodiploidy (bees). Sex-linked traits (e.g., hemophilia, color blindness) show distinctive inheritance patterns.

Genomics studies entire genomes. The human genome ($\sim 3 \times 10^9$ bp) was sequenced (2001). Only $\sim 1.5\%$ codes for proteins; the rest includes non-coding RNA genes, regulatory sequences, introns, and repetitive DNA (transposons, retrotransposons). Comparative genomics reveals evolutionary relationships.

Modern tools:

- **PCR** (polymerase chain reaction): Amplifies specific DNA sequences using thermostable DNA polymerase (Taq).
- **DNA sequencing:** Sanger (dideoxy chain-termination), next-generation (massively parallel).

- **CRISPR-Cas9:** A genome-editing tool derived from bacterial adaptive immunity. Guide RNA directs Cas9 nuclease to a specific DNA sequence, creating a double-strand break. Repair via non-homologous end joining (NHEJ) or homology-directed repair (HDR) enables gene knockout, insertion, or correction.
- **Gene cloning:** Inserting a foreign gene into a plasmid vector and transforming bacteria.
- **Gel electrophoresis:** Separates DNA fragments by size.

For review, be able to: solve monohybrid and dihybrid cross problems; explain Mendel's laws; distinguish dominance types; identify epistasis and pleiotropy; calculate recombination frequency; describe PCR steps (denature, anneal, extend); outline CRISPR-Cas9 mechanism; discuss ethical issues in genetic engineering.

Section summary Mendel's laws describe the transmission of discrete hereditary factors (genes). Extensions include epistasis, pleiotropy, linkage, and polygenic traits. Modern genomics and tools like PCR, sequencing, and CRISPR-Cas9 enable precise analysis and manipulation of genomes.

6 Biochemistry: Enzymes, Metabolism, and Energy

6.1 Core ideas

Enzymes are biological catalysts, mostly proteins (some **ribozymes** are RNA). They lower the **activation energy** (E_a) of a reaction without being consumed. The **active site** binds the **substrate**. The lock-and-key model (Fischer) and induced-fit model (Koshland) describe binding. Enzymes are highly specific and sensitive to conditions.

Reaction rate is affected by substrate concentration (Michaelis–Menten kinetics), pH, temperature, and enzyme concentration. **Cofactors** (metal ions: Zn^{2+}, Mg^{2+}) and **coenzymes** (organic: NAD^+, FAD, CoA) assist catalysis. **Vitamins** are precursors to coenzymes.

Enzyme inhibition: **Competitive inhibition** (inhibitor resembles substrate; can be overcome by high [S]). **Non-competitive inhibition** (inhibitor binds elsewhere; $V_{\max}$ decreases). **Allosteric regulation** involves binding at a regulatory site, causing conformational change. Many metabolic pathways are regulated by **feedback inhibition** (end product inhibits first committed step).

Cellular respiration (overview):

1. **Glycolysis** (cytosol): Glucose → 2 pyruvate + 2 ATP (net) + 2 NADH.
2. **Pyruvate oxidation** (mitochondrial matrix): Pyruvate → acetyl-CoA + CO_2 + NADH.
3. **Citric acid cycle** (matrix): Acetyl-CoA → 2 CO_2 + 3 NADH + $FADH_2$ + GTP (per turn).
4. **Oxidative phosphorylation** (inner mitochondrial membrane): NADH/$FADH_2$ donate electrons to the electron transport chain (ETC). Electrons flow through complexes I–IV, pumping protons (H^+) into the intermembrane space. The resulting proton gradient drives ATP synthase (**chemiosmosis**) to produce $\sim$ 30–32 ATP per glucose. O_2 is the final electron acceptor, forming H_2O.

Photosynthesis (overview):

1. **Light reactions** (thylakoid membrane): Chlorophyll absorbs photons, exciting electrons. Electron flow through photosystem II, cytochrome b_6f, photosystem I produces ATP (photophosphorylation) and NADPH. Water is split (photolysis), releasing O_2.

2. **Calvin cycle** (stroma): CO_2 is fixed by RuBisCO into 3-phosphoglycerate. Using ATP and NADPH, it is reduced to glyceraldehyde-3-phosphate (G3P), which is used to make glucose.

For review, be able to: explain how enzymes lower activation energy; interpret Michaelis–Menten and Lineweaver–Burk plots; compare competitive and non-competitive inhibition; trace glucose oxidation through glycolysis, citric acid cycle, and ETC; explain chemiosmosis; outline light reactions and Calvin cycle; define RuBisCO, photorespiration.

Section summary Enzymes accelerate biochemical reactions, with kinetics described by the Michaelis–Menten model. Cellular respiration extracts energy from glucose using glycolysis, the citric acid cycle, and oxidative phosphorylation. Photosynthesis captures light energy to fix CO_2 into organic carbon. Both processes rely on chemiosmotic ATP synthesis.

7 Evolution: Natural Selection, Populations, Speciation, and Phylogeny

7.1 Core ideas

Natural selection requires heritable variation and differential reproductive success. **Darwin's finches** (beak size correlates with seed availability; Grant and Grant, 2000s) provide a well-documented example. Types of selection: **directional** (one extreme favored), **stabilizing** (intermediate favored), **disruptive** (both extremes favored, can lead to speciation).

Population genetics studies allele frequency change. The **Hardy–Weinberg principle** describes a non-evolving population (no mutation, random mating, no selection, large population, no gene flow). Deviations indicate evolution. **Genetic drift** (random allele frequency change, especially in small populations) includes bottleneck and founder effects. **Gene flow** (migration) homogenizes populations. **Mutation** introduces new alleles. Natural selection can be quantified by **fitness** (w) and **selection coefficient** ($s = 1 - w$).

Speciation: The formation of new species. **Biological species concept** (Mayr): species are groups of interbreeding populations reproductively isolated from other such groups. **Allopatric speciation** (geographic isolation, e.g., Darwin's finches on different Galápagos islands). **Sympatric speciation** (reproductive isolation without geographic separation, e.g., polyploidy in plants). **Reproductive isolation** mechanisms: pre-zygotic (habitat, temporal, behavioral, mechanical, gametic) and post-zygotic (hybrid inviability, hybrid sterility, hybrid breakdown).

Phylogeny: Evolutionary history of a group, represented as a **cladogram** or **phylogenetic tree**. Branches represent lineages; nodes represent common ancestors. **Monophyletic** groups (clades) include an ancestor and all its descendants. **Paraphyletic** groups include an ancestor and some descendants. **Polyphyletic** groups exclude the common ancestor. Phylogenies are constructed using morphological and molecular data; **maximum parsimony** minimizes evolutionary changes.

Evidence for evolution: Fossil record (transitional forms like *Tiktaalik*), homologous structures (tetrapod limbs), vestigial structures (human appendix), comparative embryology, molecular homology (universal genetic code, conserved genes), and direct observation (antibiotic resistance in bacteria, pesticide resistance in insects).

For review, be able to: calculate allele frequencies using HW equation; distinguish selection types; explain genetic drift with examples; describe allopatric and sympatric speciation; read a phylogenetic tree; differentiate homologous vs. analogous structures; discuss the evidence for evolution.

Section summary Evolution is change in allele frequencies over generations. Natural selection, genetic drift, gene flow, and mutation drive this change. Speciation creates biodiversity, and phylogenetic trees depict the relationships among species. The evidence for evolution is overwhelming across multiple fields.

8 Diversity of Life: Microbes, Plants, Fungi, and Animals

8.1 Core ideas

The **three domains** of life (Woese, 1977, based on rRNA sequences): **Bacteria**, **Archaea**, and **Eukarya**. Bacteria and Archaea are prokaryotic; Eukarya includes eukaryotes divided into kingdoms: Protista, Plantae, Fungi, Animalia.

Bacteria: Single-celled, diverse metabolism (photoautotrophs, chemoautotrophs, heterotrophs). Gram-positive (thick peptidoglycan wall, purple stain) vs. Gram-negative (thin peptidoglycan + outer membrane, pink stain). Reproduction by binary fission. Horizontal gene transfer via transformation, conjugation, and transduction. Roles: nutrient cycling (nitrogen fixation by *Rhizobium*), pathogens (*Mycobacterium tuberculosis*, *E. coli* O157:H7), beneficial microbiota.

Archaea: Often extremophiles (thermophiles, halophiles, methanogens). Distinct membrane lipids (isoprenoid ether-linked). Key in biogeochemical cycles.

Protists: Paraphyletic group of mostly unicellular eukaryotes. Examples: *Amoeba* (phagocytosis), *Paramecium* (cilia), *Plasmodium* (malaria), algae (photosynthetic).

Fungi: Heterotrophs that absorb nutrients externally (osmotrophy). Cell walls contain chitin. Body is a mycelium of hyphae. Reproduction via spores (sexual and asexual). Roles: decomposers, mutualists (mycorrhizae with plant roots, lichens), pathogens (athlete's foot, *Candida*). Major groups: zygomycetes (bread mold), ascomycetes (yeasts, morels), basidiomycetes (mushrooms).

Plants: Autotrophs with cellulose cell walls and chloroplasts. Alternation of generations: **gametophyte** (haploid, produces gametes) and **sporophyte** (diploid, produces spores). Major groups:

- **Bryophytes** (mosses): Non-vascular, gametophyte dominant.
- **Pteridophytes** (ferns): Vascular, sporophyte dominant, no seeds.
- **Gymnosperms** (conifers): Vascular, seeds (naked on cones), pollen.
- **Angiosperms** (flowering plants): Vascular, seeds enclosed in fruit, flowers for pollination. Monocots (one cotyledon, parallel veins) vs. dicots/eudicots (two cotyledons, netted veins).

Animals: Multicellular heterotrophs that ingest food. Key features: symmetry (radial vs. bilateral), body cavities (acoelomate, pseudocoelomate, coelomate), protostome vs. deuterostome development (determines fate of blastopore). Major phyla:

- Porifera (sponges)
- Cnidaria (jellyfish, corals)
- Platyhelminthes (flatworms)
- Nematoda (roundworms)
- Annelida (segmented worms)
- Mollusca (snails, clams, octopus)

- Arthropoda (insects, crustaceans, arachnids) – most diverse animal phylum
- Echinodermata (starfish)
- Chordata – vertebrates (fish, amphibians, reptiles, birds, mammals)

For review, be able to: compare the three domains; distinguish Gram-positive and Gram-negative bacteria; explain alternation of generations; identify major plant groups; list key animal phyla with distinguishing characteristics; describe fungal reproduction; explain endosymbiosis in origin of eukaryotes.

Section summary Life's diversity is classified into three domains and multiple kingdoms. Bacteria and Archaea encompass prokaryotic diversity; Eukarya includes protists, fungi, plants, and animals, each with unique adaptations. Phylogenetic classification reflects evolutionary relationships.

9 The Organism: Development, Physiology, Nervous System, Immunity, and Reproduction

9.1 Core ideas

Development: From a single-celled zygote to a multicellular organism. Key processes: **cell division**, **differentiation** (cells become specialized), **morphogenesis** (organization into tissues and organs). In animals, early development includes cleavage (rapid mitotic divisions), blastula formation, gastrulation (formation of three germ layers: ectoderm, mesoderm, endoderm), and organogenesis. **Homeobox** (Hox) genes control body plan patterning across animals (discovered in *Drosophila*, Lewis, Nüsslein-Volhard, Wieschaus, Nobel 1995).

Physiology: How organ systems function. **Homeostasis** is maintained by negative feedback loops (e.g., body temperature: hypothalamus triggers shivering or sweating). Key systems: circulatory (heart pumps blood through vessels; gas exchange in capillaries), respiratory (lungs, alveoli, O_2/CO_2 exchange by diffusion), digestive (mouth to anus; enzymes break down food; small intestine absorbs nutrients), excretory (kidneys filter blood, produce urine; regulate water and ion balance), endocrine (hormones from glands; insulin/glucagon regulate blood glucose).

Nervous system: Neurons transmit electrical signals. The **resting potential** (~ -70 mV) is maintained by Na^+/K^+-ATPase and K^+ leak channels. An action potential occurs when depolarization reaches threshold: voltage-gated Na^+ channels open (rapid depolarization), then K^+ channels open (repolarization). The signal propagates down the axon. At the synapse, neurotransmitters (acetylcholine, dopamine, serotonin, GABA, glutamate) are released, binding to postsynaptic receptors. The central nervous system (brain, spinal cord) integrates information; the peripheral nervous system (sensory, motor, autonomic) connects to the body.

Immune system: Defends against pathogens through layered defenses. **Innate immunity** is the first line: physical barriers (skin, mucous membranes), chemical barriers (lysozyme in tears, stomach acid), and cellular responses (phagocytes such as macrophages and neutrophils that engulf invaders; natural killer cells that destroy virus-infected cells; dendritic cells that bridge innate and adaptive immunity). The **complement system** is a cascade of plasma proteins that opsonize pathogens, recruit inflammatory cells, and form membrane-attack complexes (MACs) to lyse bacteria. **Inflammation** is a localized response to injury or infection: vasodilation increases blood flow (redness and heat), increased vascular permeability allows fluid and immune cells to enter tissues (swelling), and pain signals alert the organism.

Adaptive immunity is antigen-specific and develops memory. It has two branches. **Humoral immunity** (B cells): B cell receptors (membrane-bound antibodies) bind specific antigens. Upon activation, B cells proliferate and differentiate into plasma cells (antibody factories) and memory B cells. **Cell-mediated immunity** (T cells): **Helper T cells** ($CD4^+$)

coordinate the response by releasing cytokines; **cytotoxic T cells** ($CD8^+$) kill infected host cells displaying foreign antigens on MHC class I. **Antigen presentation** is central: dendritic cells and macrophages present processed antigens on **MHC class II** molecules to helper T cells; infected cells display endogenous antigens on **MHC class I** to cytotoxic T cells. This dual MHC system ensures that the immune system distinguishes self from non-self.

Antibodies (immunoglobulins) are Y-shaped proteins with two identical heavy chains and two identical light chains. Each arm has a variable region (the antigen-binding site, or paratope) and a constant region (determining effector function). There are five classes: **IgM** (first produced in primary response, pentameric), **IgG** (most abundant in blood, crosses placenta), **IgA** (mucosal surfaces), **IgE** (allergic responses, parasite defense), and **IgD** (B cell receptor). **Clonal selection** is the core mechanism: when a lymphocyte encounters its specific antigen, it is selected to proliferate, producing a clone of effector cells and memory cells. **Vaccination** exploits this by presenting a harmless antigen (attenuated pathogen, inactivated toxin, or subunit) to prime the immune system without causing disease, generating immunological memory so that a future encounter with the real pathogen triggers a faster, stronger secondary response.

Reproduction: Asexual (binary fission, budding, fragmentation, parthenogenesis) produces genetically identical offspring. **Sexual** reproduction involves meiosis (reduction division) and fertilization, generating genetic variation. **Meiosis I** separates homologous chromosomes (reduces ploidy); **Meiosis II** separates sister chromatids. Crossing over in prophase I and independent assortment generate diversity. Human reproduction: spermatogenesis (testes) and oogenesis (ovaries); menstrual cycle regulated by hormones (FSH, LH, estrogen, progesterone).

For review, be able to: outline embryonic development stages; explain Hox gene function; diagram a negative feedback loop; describe an action potential (resting, depolarization, repolarization, refractory period); contrast innate and adaptive immunity; explain clonal selection; compare mitosis and meiosis; trace the human menstrual cycle.

Section summary Development transforms a zygote into a complex organism through regulated gene expression. Physiological systems maintain homeostasis. The nervous system uses electrical and chemical signals for rapid communication. The immune system discriminates self from non-self. Sexual reproduction generates genetic variation via meiosis and fertilization.

10 Ecology: Populations, Communities, Ecosystems, and Conservation

10.1 Core ideas

Population ecology studies the dynamics of populations of a single species. **Population size** (N) changes via births, deaths, immigration, emigration. **Exponential growth** (unlimited resources): $dN/dt = rN$, where r is the intrinsic growth rate. **Logistic growth** (with carrying capacity K): $dN/dt = rN(1 - N/K)$. Life history strategies: **r-selected** (many small offspring, little parental care) vs. **K-selected** (few large offspring, extensive care). **Population age structure** (pyramid, bell-shaped, urn-shaped) predicts growth trends.

Community ecology examines interactions among species:

- **Competition** (−/−): **Competitive exclusion principle** (two species cannot occupy the same niche indefinitely). Resource partitioning reduces competition (character displacement).
- **Predation** (+/−): Predator–prey cycles (Lotka–Volterra equations). Defenses: crypticity, aposematic coloration, mimicry (Batesian: harmless mimics toxic; Müllerian: two toxic species resemble each other).

- **Symbiosis**: **Mutualism** (+/+, e.g., pollinators and flowers), **Commensalism** (+/0, e.g., barnacles on whales), **Parasitism** (+/−, e.g., tapeworms).

- **Keystone species** has a disproportionately large effect (e.g., sea otters controlling sea urchins). **Biodiversity** and **ecosystem stability** are positively correlated.

Ecosystem ecology studies energy flow and nutrient cycling. **Food chains** and **food webs** map trophic relationships. **Trophic levels**: producers (autotrophs) → primary consumers (herbivores) → secondary consumers (carnivores) → tertiary consumers. Only $\sim 10\%$ of energy transfers between levels (ecological efficiency, Lindeman). Nutrients (C, N, P, H_2O) cycle through biotic and abiotic reservoirs. The **carbon cycle** includes photosynthesis, respiration, decomposition, combustion, and fossil fuel burning. The **nitrogen cycle** involves fixation, nitrification, assimilation, ammonification, denitrification.

Conservation biology: Habitat loss is the primary threat to biodiversity. Other threats: overexploitation, invasive species, pollution, climate change. **Island biogeography** theory (MacArthur and Wilson, 1967): species richness on an island reflects a balance between immigration and extinction rates, determined by island size and distance from mainland. Conservation strategies: protected areas, habitat corridors, captive breeding, restoration ecology.

For review, be able to: solve exponential and logistic growth problems; apply the Lotka–Volterra competition and predation models; explain trophic transfer efficiency; diagram the carbon and nitrogen cycles; use island biogeography theory; discuss major conservation threats.

Section summary Ecology studies interactions across scales: populations (growth and regulation), communities (competition, predation, mutualism), and ecosystems (energy flow, nutrient cycling). Conservation biology applies ecological principles to protect biodiversity in the face of human-caused change.

11 Experiments and Data: Analytical Methods, Statistics, and Ethics

11.1 Core ideas

The scientific method: observation, hypothesis formulation, prediction, experimentation, analysis, conclusion, replication. Hypotheses must be **falsifiable** (Popper). The **null hypothesis** (H_0) states no effect; the alternative (H_A) states an effect. Experiments require **controls** (positive, negative), **randomization**, and **replication**. **Blinding** (single or double) prevents bias. **Correlation** does not imply causation.

Types of data: Categorical (nominal, ordinal) and **numerical** (discrete, continuous). **Descriptive statistics** summarize data: mean, median, mode, variance (s^2), standard deviation (s), range, interquartile range. **Standard error** (SEM $= s/\sqrt{n}$) estimates sampling variability. Confidence intervals (95% CI $\approx \bar{x} \pm 1.96 \times$ SEM) indicate precision.

Hypothesis testing:

- **t-test:** compares two group means (paired or unpaired, equal or unequal variance).

- **ANOVA:** compares three or more group means (one-way, two-way). Post-hoc tests (Tukey, Bonferroni) identify specific differences.

- **Chi-square (χ^2) test:** tests association between categorical variables, or goodness-of-fit to expected ratios (e.g., Mendelian 3:1).

- **Correlation:** Pearson r (linear relationship) or Spearman ρ (monotonic). Ranges -1 to $+1$.

- **Regression:** Linear regression $y = mx + b$ models how y changes with x. R^2 indicates proportion of variance explained.

The **p-value** is the probability of observing data as extreme as collected, assuming H_0 is true. $\alpha = 0.05$ is the conventional significance threshold. **Type I error** (false positive, α) vs. **Type II error** (false negative, β). **Statistical power** $(1 - \beta)$ increases with sample size and effect size.

Common techniques in biology:

- **Microscopy:** light (brightfield, phase-contrast, fluorescence, confocal) and electron (SEM, TEM).
- **Chromatography:** separates molecules by affinity or size.
- **Spectrophotometry:** measures light absorbance; used for quantification (Beer–Lambert law: $A = \varepsilon cl$).
- **Electrophoresis:** separates DNA, RNA, or proteins by size/charge.
- **Immunoassays:** ELISA (enzyme-linked immunosorbent assay) detects specific proteins.
- **Sequencing:** Sanger and NGS determine DNA sequence.

Research ethics: Informed consent, minimizing harm, animal welfare (3Rs: Replacement, Reduction, Refinement), conflicts of interest, data fabrication/falsification (fraud: e.g., Hwang Woo-suk stem cell scandal). **Responsible conduct of research** includes careful record-keeping, transparent reporting, and peer review. **Bioethics** issues: genetic engineering, cloning, stem cell research, human subjects protections, environmental ethics.

For review, be able to: design a controlled experiment; calculate and interpret descriptive statistics; choose and apply the appropriate statistical test; interpret p-values and confidence intervals; explain common lab techniques; discuss ethical principles in research; avoid common statistical pitfalls (p-hacking, multiple comparisons, small sample bias).

Section summary Rigorous experimental design, appropriate statistical analysis, and ethical conduct are the foundation of reliable biological research. Understanding the tools and methods – from microscopy to sequencing to statistical tests – is essential for interpreting scientific claims and producing reproducible knowledge.