

MCAT Master Review Packet

Formulas, terminology, and high-yield content for all four sections

Aligned to the AAMC "What's on the MCAT Exam?" content outline



- **Chemical & Physical Foundations**
Math · Physics · General Chemistry · Organic Chemistry
- **Critical Analysis & Reasoning Skills**
Passage strategy · Question types · Answer traps
- **Biological & Biochemical Foundations**
Biochemistry · Cell & Molecular Bio · Organ Systems
- **Psychological, Social & Biological Foundations**
Psychology · Sociology · Research & Statistics

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START HERE

How to Use This Packet

This packet condenses the content the MCAT tests into one reference: the equations you must know cold, the vocabulary that shows up in passages, and the relationships between concepts that test writers like to probe. It is built for **review**, not first-time learning. Use it to find gaps, then go deeper with a textbook, a tutor, or official practice material. Every section is organized around the AAMC's official content outline, so nothing here is filler.

The Exam at a Glance

Section	Questions	Time	Score range	What it emphasizes
Chemical & Physical Foundations of Biological Systems (C/P)	59	95 min	118-132	Gen chem, physics, orgo and biochem applied to living systems
Critical Analysis & Reasoning Skills (CARS)	53	90 min	118-132	Humanities and social-science passages; no outside knowledge required
Biological & Biochemical Foundations of Living Systems (B/B)	59	95 min	118-132	Biology and biochemistry, with some gen chem and orgo
Psychological, Social & Biological Foundations of Behavior (P/S)	59	95 min	118-132	Intro psychology and sociology, with biology of behavior

- **Total score:** 472-528, with the midpoint around 500. Seated time is about 7.5 hours including optional breaks; total content time is 6 hours 15 minutes.
- **No calculator.** A periodic table is provided. Expect to estimate, round, and work in scientific notation.
- **Format:** each science section has 10 passage-based sets (4 to 6 questions each) plus 15 independent (discrete) questions. CARS has 9 passage sets of 5 to 7 questions.
- Exam logistics can change. Confirm current details, fees, and test dates at the AAMC website before you register.

What the AAMC Actually Tests

The AAMC publishes approximate weightings for every section. Use them to decide where your study hours go. Biochemistry is about 25% of **both** science sections, which makes it the highest-leverage subject on the exam.

Section	Disciplines	Foundational concepts
C/P	General chemistry 30%, biochemistry 25%, physics 25%, organic chemistry 15%, biology 5%	FC 4 (physical principles) 40%; FC 5 (chemical principles) 60%
B/B	Biology 65%, biochemistry 25%, general chemistry 5%, organic chemistry 5%	FC 1 (biomolecules) 55%; FC 2 (cells) 20%; FC 3 (organ systems) 25%
P/S	Psychology 65%, sociology 30%, biology 5%	FC 6: 25%; FC 7: 35%; FC 8: 20%; FC 9: 15%; FC 10: 5%
CARS	Humanities 50%, social sciences 50%	Foundations of Comprehension 30%; Reasoning Within the Text 30%; Reasoning Beyond the Text 40%

Scientific inquiry skill (all three science sections)	Share	What it looks like
Skill 1: Knowledge of Scientific Concepts and Principles	35%	Recall and recognize a concept, equation, or relationship
Skill 2: Scientific Reasoning and Problem-Solving	45%	Apply concepts to predict, explain, or calculate
Skill 3: Reasoning About the Design and Execution of Research	10%	Variables, controls, sampling, ethics
Skill 4: Data-Based and Statistical Reasoning	10%	Read figures and tables; draw supported conclusions

Percentages are rounded to the nearest 5% by the AAMC and vary slightly from one test form to another.

A Simple Review Method

Step	What to do
1. Diagnose	Take a full-length practice test under timed conditions before reviewing content. Record section scores.
2. Triage	Use this packet's tables to mark each topic green (know it), yellow (shaky), or red (don't know).
3. Learn reds and yellows	Study the underlying concept, then do 10–20 practice questions on that topic.
4. Consolidate	Turn every missed question into a flashcard or a line in an error log: why you missed it and the rule that fixes it.
5. Simulate	In the final 4–6 weeks, take full-lengths weekly on the same schedule as test day and spend as long reviewing as testing.

Sample 12-Week Timeline

Weeks	Focus	Practice
1–2	Diagnostic; biochemistry and general chemistry fundamentals; begin daily CARS	Topic question sets; 2 CARS passages/day
3–4	Physics, organic chemistry, math skills	Mixed science sets; start error log
5–6	Biology organ systems, molecular biology, genetics	Section-length practice; flashcards daily
7–8	Psychology and sociology; research methods and statistics	First scheduled full-length; deep review
9–10	Targeted weak areas from full-length data	1 full-length/week plus targeted sets
11–12	Official practice exams; taper in final days	Full-lengths at test-day times; light review the last 2 days

SECTION 1

Math Toolkit for a Calculator-Free Exam

Scientific Notation and Estimation

- **Multiply:** add exponents. $(3 \times 10^4)(2 \times 10^{-6}) = 6 \times 10^{-2}$
- **Divide:** subtract exponents. $(8 \times 10^5)/(4 \times 10^2) = 2 \times 10^3$
- **Square root:** make the exponent even first. $\sqrt{4 \times 10^{-7}} = \sqrt{40 \times 10^{-8}} \approx 6.3 \times 10^{-4}$
- Round aggressively when answer choices differ by a factor of 2 or more; track whether you rounded up or down.

Significant Figures and Units

- **Multiplying or dividing:** keep the fewest significant figures of any input.
- **Adding or subtracting:** keep the fewest decimal places of any input.
- **Dimensional analysis:** carry units through every step; if the units of your answer are wrong, the setup is wrong. Conversion factors between metric and English units are provided on the exam when needed.

Logarithms

Rule / value	Use
$\log(ab) = \log a + \log b$	Splitting concentrations for pH
$\log(a/b) = \log a - \log b$	Henderson-Hasselbalch, Nernst
$\log(a^n) = n \cdot \log a$	Decibel and pH scaling
$\log 1 = 0$; $\log 2 \approx 0.30$; $\log 3 \approx 0.48$; $\log 5 \approx 0.70$; $\log 10 = 1$	Quick estimates
$\ln x \approx 2.303 \log x$	Converting $\Delta G^\circ = -RT \ln K$ to base 10
$-\log(a \times 10^{-b}) = b - \log a$	e.g., $[H^+] = 3 \times 10^{-5} \rightarrow \text{pH} \approx 5 - 0.48 \approx 4.5$

Reading Linear, Semilog, and Log-Log Graphs

Plot type	What becomes a straight line	MCAT examples
Linear	$y = mx + b$; slope = $\Delta y / \Delta x$	Ohm's law, Lineweaver-Burk
Semilog (one log axis)	Exponential relationships, $y = Ae^{kx}$	Radioactive decay, first-order kinetics, bacterial growth
Log-log (both axes log)	Power laws, $y = ax^n$; slope = the exponent n	Poiseuille ($Q \propto r^4$), Coulomb ($F \propto r^{-2}$)

On a log axis, each major tick usually represents a 10-fold change. Read values carefully between ticks: the midpoint between 10 and 100 is about 30, not 55.

Trigonometry

θ	0°	30°	45°	60°	90°	180°
sin θ	0	0.5	≈ 0.71	≈ 0.87	1	0
cos θ	1	≈ 0.87	≈ 0.71	0.5	0	-1
tan θ	0	≈ 0.58	1	≈ 1.73	undefined	0

SOH-CAH-TOA: sin = opposite/hypotenuse, cos = adjacent/hypotenuse, tan = opposite/adjacent. $\sqrt{2} \approx 1.41$; $\sqrt{3} \approx 1.73$. In a 30-60-90 triangle the sides are 1 : $\sqrt{3}$: 2; in a 45-45-90 triangle they are 1 : 1 : $\sqrt{2}$.

Metric Prefixes and Conversions

Prefix	Symbol	Factor	Prefix	Symbol	Factor
tera	T	10^{12}	deci	d	10^{-1}
giga	G	10^9	centi	c	10^{-2}
mega	M	10^6	milli	m	10^{-3}
kilo	k	10^3	micro	μ	10^{-6}
			nano	n	10^{-9}
			pico	p	10^{-12}

- $1 \text{ \AA} = 10^{-10} \text{ m}$; $1 \text{ nm} = 10 \text{ \AA}$
- $1 \text{ L} = 1000 \text{ cm}^3 = 10^{-3} \text{ m}^3$; $1 \text{ mL} = 1 \text{ cm}^3$
- $1 \text{ atm} = 760 \text{ mmHg} = 760 \text{ torr} = 101.3 \text{ kPa}$
- $1 \text{ cal} = 4.184 \text{ J}$; $1 \text{ food Calorie} = 1 \text{ kcal}$
- $T(\text{K}) = T(^{\circ}\text{C}) + 273$; $T(^{\circ}\text{F}) = 1.8 \cdot T(^{\circ}\text{C}) + 32$
- $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$

Proportional Reasoning

Many questions ask what happens to one variable when another changes. Isolate the variable, then scale. If $F = kq_1q_2/r^2$ and r triples, F becomes 1/9 as large. If Poiseuille flow depends on r^4 and radius halves, flow falls to 1/16.

SECTION 2

Physics

Essential Constants

Constant	Value
Gravitational acceleration, g	9.8 m/s ² (use 10 for estimates)
Speed of light, c	3.0×10^8 m/s
Elementary charge, e	1.6×10^{-19} C
Coulomb's constant, $k = 1/(4\pi\epsilon_0)$	9.0×10^9 N·m ² /C ²
Planck's constant, h	6.63×10^{-34} J·s
Avogadro's number, N_A	6.02×10^{23} mol ⁻¹
Gas constant, R	8.314 J/(mol·K) = 0.0821 L·atm/(mol·K)
Faraday's constant, F	96,485 C/mol e ⁻ ($\approx 10^5$)
Density of water	1000 kg/m ³ = 1 g/cm ³
Speed of sound in air	≈ 343 m/s at room temperature

Vectors vs Scalars

A **scalar** has magnitude only; a **vector** has magnitude and direction, so vectors cannot be added like ordinary numbers.

Scalars	Vectors
Distance, speed, mass, time, energy, work, power, temperature, charge, pressure, electric potential	Displacement, velocity, acceleration, force, momentum, impulse, torque, electric field, magnetic field

- **Components:** $A_x = A \cos \theta$, $A_y = A \sin \theta$ (θ measured from the x-axis). Magnitude = $\sqrt{A_x^2 + A_y^2}$; direction: $\tan \theta = A_y/A_x$.
- **Adding:** add x-components and y-components separately, then recombine. Graphically, place vectors tip to tail.
- **Subtracting:** $A - B = A + (-B)$; flip B's direction and add.
- **Bounds check:** the resultant of A and B always lies between $|A - B|$ (opposite directions) and $A + B$ (same direction).
- **Distance vs displacement:** one 400 m lap on a track is 400 m of distance but 0 m of displacement, so average velocity is 0 even though average speed is not.
- **Right-hand rule ($\mathbf{F} = q\mathbf{vB}$):** point your fingers along $\mathbf{v}$ and curl them toward $\mathbf{B}$; your thumb gives the force on a positive charge. Flip the answer for an electron. For a current-carrying wire, point your thumb along $\mathbf{I}$ and your fingers curl in the direction of $\mathbf{B}$.
- The AAMC requires vector addition, subtraction, and the right-hand rule, but not dot or cross products.

WORKED EXAMPLE

3 N east plus 4 N north: magnitude = $\sqrt{9 + 16} = 5$ N; direction: $\tan \theta = 4/3$, so $\theta \approx 53^\circ$ north of east.

Kinematics

Equation	Missing variable / notes
$v = v_0 + at$	No displacement
$\Delta x = v_0 t + \frac{1}{2}at^2$	No final velocity
$v^2 = v_0^2 + 2a\Delta x$	No time
$\Delta x = \frac{1}{2}(v_0 + v)t$	No acceleration
Projectile: $v_x = v \cos \theta$ (constant); $v_y = v \sin \theta$ ($a = -g$)	Horizontal and vertical motions are independent
Free-fall time from height h: $t = \sqrt{(2h/g)}$	Horizontal launch speed doesn't change fall time

- At the peak of a projectile's path, $v_y = 0$ but $a = -g$. Range is maximized at 45° (no air resistance).
- Slope of x-t graph = velocity; slope of v-t graph = acceleration; area under v-t graph = displacement.

Forces and Newton's Laws

Concept	Formula / statement
First law (inertia)	No net force $\rightarrow$ constant velocity
Second law	$F_{\text{net}} = ma$
Third law	Forces come in equal and opposite pairs acting on different objects
Weight	$W = mg$
Friction	$f_s \leq \mu_s N$; $f_k = \mu_k N$; $\mu_s > \mu_k$
Inclined plane	Parallel component = $mg \sin \theta$; normal force = $mg \cos \theta$
Universal gravitation	$F = Gm_1m_2/r^2$
Centripetal acceleration and force	$a_c = v^2/r$; $F_c = mv^2/r$ (directed toward center)
Torque	$\tau = rF \sin \theta$; equilibrium when $\Sigma \tau = 0$ and $\Sigma F = 0$
Center of mass	$x_{\text{cm}} = \Sigma(m \cdot x) / \Sigma m$; gravity acts as if all mass sits there
Hooke's law	$F = -kx$

Work, Energy, Power, Momentum

Quantity	Formula	Units / notes
Work	$W = Fd \cos \theta$	Joules ($J = N \cdot m$); only the force component along displacement does work
Kinetic energy	$KE = \frac{1}{2}mv^2$	Doubling v quadruples KE
Gravitational PE	$PE = mgh$	
Elastic PE	$PE = \frac{1}{2}kx^2$	
Work-energy theorem	$W_{\text{net}} = \Delta KE$	
Conservation of energy	$KE_i + PE_i = KE_f + PE_f$	Only if no non-conservative forces (e.g., friction)
Power	$P = W/t = Fv$	Watts (J/s)
Momentum	$p = mv$	Always conserved in a closed system

Quantity	Formula	Units / notes
Impulse	$J = F\Delta t = \Delta p$	Longer contact time $\rightarrow$ smaller force
Mechanical advantage	$MA = F_{\text{out}}/F_{\text{in}}$	Pulleys, levers, ramps reduce force but not work

HIGH-YIELD TIP

Elastic collisions conserve both momentum and kinetic energy. Inelastic collisions conserve momentum only. In a perfectly inelastic collision, objects stick together: $m_1v_1 + m_2v_2 = (m_1 + m_2)v_f$.

Periodic Motion

- Amplitude** is maximum displacement; **frequency** (Hz) is cycles per second; **period** $T = 1/f$; **phase** describes where in the cycle a wave is (two waves 180° out of phase cancel).
- Mass on a spring: $T = 2\pi\sqrt{m/k}$. Simple pendulum: $T = 2\pi\sqrt{L/g}$ (independent of mass).

Fluids

Concept	Formula	Notes
Density	$\rho = m/V$	Specific gravity = ρ/ρ_{water}
Pressure	$P = F/A$	1 Pa = 1 N/m ²
Hydrostatic (absolute) pressure	$P = P_0 + \rho gh$	Gauge pressure = ρgh
Buoyant force (Archimedes)	$F_B = \rho_{\text{fluid}} \cdot V_{\text{submerged}} \cdot g$	Fraction submerged = $\rho_{\text{object}}/\rho_{\text{fluid}}$
Pascal's principle	$F_1/A_1 = F_2/A_2$	Hydraulic lifts
Continuity	$A_1v_1 = A_2v_2$	Narrower pipe $\rightarrow$ faster flow
Bernoulli	$P + \frac{1}{2}\rho v^2 + \rho gh = \text{constant}$	Faster flow $\rightarrow$ lower pressure (Venturi effect); pitot tubes measure flow speed from this pressure difference
Poiseuille's law	$Q = \pi r^4 \Delta P / (8\eta L)$	Radius dominates; applies to viscous laminar flow

- Cohesion** (like molecules attract) produces surface tension; **adhesion** (unlike molecules) produces capillary rise and a concave meniscus in water.
- Blood vessels: total cross-sectional area is greatest in capillaries, so velocity is slowest there, allowing exchange.
- Turbulence:** above a critical velocity (high Reynolds number), smooth laminar flow breaks into eddies. Turbulent blood flow is heard as a bruit or murmur.
- Mercury barometer:** atmospheric pressure supports a 760 mm column of Hg at sea level.

Electrostatics

Quantity	Formula	Notes
Coulomb's law	$F = kq_1q_2/r^2$	Like charges repel
Electric field	$E = F/q = kQ/r^2$	Points away from +, toward -; $N/C = V/m$
Electric potential	$V = kQ/r$	Scalar; volts (J/C)
Potential energy	$U = kq_1q_2/r = qV$	Systems move toward lower U

Quantity	Formula	Notes
Work by field	$W = q\Delta V$	Positive charges move from high to low V
Parallel plates	$E = V/d$	Uniform field
Dipole moment	$p = qd$	Physics: points – to +. Chemistry draws the dipole arrow toward the δ^- (more electronegative) atom, the opposite direction

Equipotential lines are perpendicular to field lines; no work is done moving a charge along an equipotential. **Conductors** let charge move freely (excess charge sits on the surface); **insulators** hold charge in place.

Circuits

Quantity	Formula / rule
Ohm's law	$V = IR$
Current	$I = \Delta Q/\Delta t$ (amperes); conventional current flows the way positive charge would move
Resistance of a wire	$R = \rho L/A$ (longer, thinner $\rightarrow$ more resistance)
Power	$P = IV = I^2R = V^2/R$
Resistors in series	$R_{eq} = R_1 + R_2 + \dots$ (same current)
Resistors in parallel	$1/R_{eq} = 1/R_1 + 1/R_2 + \dots$ (same voltage; $R_{eq} < \text{smallest } R$)
Capacitance	$C = Q/V$; $C = \kappa\epsilon_0 A/d$
Capacitor energy	$U = \frac{1}{2}CV^2 = \frac{1}{2}QV = Q^2/(2C)$
Kirchhoff's laws	Junction: $\Sigma I_{in} = \Sigma I_{out}$. Loop: $\Sigma \Delta V = 0$
AC circuits	$V_{rms} = V_{max}/\sqrt{2}$; $I_{rms} = I_{max}/\sqrt{2}$

- Ammeters go in series (ideal resistance ≈ 0); voltmeters go in parallel (ideal resistance $\approx \infty$).
- Inserting a dielectric increases capacitance by factor κ . If the battery stays connected, V is fixed and Q increases; if disconnected, Q is fixed and V decreases.
- Conductance is $1/R$ (siemens). **Metallic conduction** uses delocalized electrons and falls as temperature rises; **electrolytic conduction** uses mobile ions and rises with ion concentration.

Capacitors in Circuits

Capacitors combine in the opposite way from resistors because parallel plates effectively add area ($C \propto A$) while series plates effectively add separation ($C \propto 1/d$).

	Series	Parallel
Shared quantity	Same charge Q on each	Same voltage V across each
What adds	Voltages: $V_{total} = V_1 + V_2$	Charges: $Q_{total} = Q_1 + Q_2$
Equivalent capacitance	$1/C_{eq} = 1/C_1 + 1/C_2$ (C_{eq} smaller than the smallest)	$C_{eq} = C_1 + C_2$
Two equal capacitors C	$C/2$	$2C$

WORKED EXAMPLE

2 μF and 6 μF capacitors on a 12 V battery.

Series: $1/C_{\text{eq}} = 1/2 + 1/6 = 4/6$, so $C_{\text{eq}} = 1.5 \mu\text{F}$ and $Q = C_{\text{eq}} \cdot V = 18 \mu\text{C}$ on each. $V = Q/C$ gives 9 V across the 2 μF and 3 V across the 6 μF : the smaller capacitor takes the larger voltage. Stored energy = $\frac{1}{2}(1.5 \mu\text{F})(12 \text{ V})^2 = 108 \mu\text{J}$.

Parallel: $C_{\text{eq}} = 8 \mu\text{F}$; each sits at 12 V, holding 24 μC and 72 μC (96 μC total).

- Mixed networks: collapse parallel groups into one capacitor, then combine in series (and repeat).
- In a DC circuit at steady state, a fully charged capacitor carries no current and behaves like a break in the wire.

Magnetism

Quantity	Formula	Notes
Force on a moving charge	$F = qvB \sin \theta$	Right-hand rule; $F \perp v$, so magnetic force does no work
Force on a wire	$F = ILB \sin \theta$	
Field around a straight wire	$B = \mu_0 I / (2\pi r)$	Curl fingers around wire, thumb along current
Circular motion in a B field	$r = mv / (qB)$	Basis of mass spectrometry

Diamagnetic materials are weakly repelled (all electrons paired); paramagnetic materials are weakly attracted (unpaired electrons); ferromagnetic materials are strongly attracted (e.g., Fe, Ni, Co). SI unit of B: tesla (T).

Waves and Sound

Concept	Formula / fact
Wave speed	$v = f\lambda$; period $T = 1/f$
Sound intensity level	$\beta = 10 \log(I/I_0)$, $I_0 = 10^{-12} \text{ W/m}^2$; $\times 10$ intensity = +10 dB
Intensity vs distance	$I \propto 1/r^2$
Doppler effect	$f' = f(v \pm v_D) / (v \mp v_S)$; use top signs when moving toward each other
Strings and open pipes	$\lambda = 2L/n$, $f = nv / (2L)$, $n = 1, 2, 3, \dots$
Pipe closed at one end	$\lambda = 4L/n$, $f = nv / (4L)$, $n = 1, 3, 5, \dots$ (odd harmonics only)
Beat frequency	$f_{\text{beat}} = f_1 - f_2 $
Speed of sound	Fastest in solids, slowest in gases; $v = \sqrt{B/\rho}$

- Transverse waves oscillate perpendicular to propagation (light); longitudinal waves oscillate parallel (sound).
- Constructive interference: waves in phase, amplitudes add. Destructive: 180° out of phase, amplitudes cancel.
- Human hearing: $\sim 20 \text{ Hz}$ – 20 kHz . Ultrasound $> 20 \text{ kHz}$; used in imaging via reflection and Doppler.
- Attenuation** (damping) reduces amplitude over distance. A **shock wave** forms when a source moves faster than sound (sonic boom).

Light and Optics

Concept	Formula / fact
Electromagnetic wave	$c = f\lambda$; photon energy $E = hf = hc/\lambda$
Visible spectrum	≈ 400 nm (violet) to 700 nm (red); ROYGBIV from long to short λ
Index of refraction	$n = c/v$ ($n \geq 1$)
Snell's law	$n_1 \sin \theta_1 = n_2 \sin \theta_2$; light bends toward normal entering higher n
Critical angle	$\sin \theta_c = n_2/n_1$ (only when going from higher to lower n)
Thin lens / mirror equation	$1/f = 1/o + 1/i$
Magnification	$m = -i/o$; $ m > 1$ enlarged; negative $m \rightarrow$ inverted
Mirror focal length	$f = R/2$
Lens power	$P = 1/f$ (diopters, f in meters); lenses in contact: $P_{\text{total}} = \Sigma P$

Device	f sign	Image behavior
Converging (convex) lens / concave mirror	+	Real & inverted if object beyond f ; virtual & upright if inside f
Diverging (concave) lens / convex mirror	–	Always virtual, upright, reduced

MNEMONIC

Sign rule: real images are positive ($i > 0$) and inverted; virtual images are negative and upright. Real images form where light actually goes: in front of mirrors, behind lenses.

Vision: myopia (nearsighted) is corrected with diverging lenses; hyperopia (farsighted) with converging lenses.

- **Total internal reflection:** going from higher to lower n at an angle beyond θ_c , all light reflects (fiber optics, endoscopes).
- **Dispersion:** n varies with λ , so prisms separate colors (violet bends most).
- **Lens aberrations:** spherical (edge rays focus at a different point than central rays) and chromatic (dispersion focuses colors at different points).
- **Diffraction:** single slit minima at $\sin \theta = n\lambda$. Double slit (Young) maxima at $d \sin \theta = m\lambda$. Thin films and diffraction gratings work by the same interference; X-ray diffraction reveals molecular structure.
- **Polarization:** plane-polarized light oscillates in one plane; circularly polarized light is used in circular dichroism.
- Electromagnetic waves are perpendicular, oscillating electric and magnetic fields; propagation is perpendicular to both.

Atomic and Nuclear Physics

Concept	Formula / fact
Photoelectric effect	$KE_{\text{max}} = hf - \phi$ (ϕ = work function); intensity changes number of electrons, not their KE
Bohr hydrogen energy levels	$E_n = -13.6 \text{ eV}/n^2$; emission when electrons fall, absorption when they rise
Heisenberg uncertainty	$\Delta x \cdot \Delta p \geq h/4\pi$: position and momentum cannot both be known exactly
Mass-energy	$E = mc^2$; mass defect = binding energy/ c^2

Concept	Formula / fact
Half-life	$N = N_0(1/2)^{t/t_{1/2}}$; after 3 half-lives, 12.5% remains
Exponential decay	$N = N_0e^{-\lambda t}$; $t_{1/2} = 0.693/\lambda$

Decay	Emitted	Change in A (mass #)	Change in Z (atomic #)
Alpha (α)	${}^4_2\text{He}$ nucleus	-4	-2
Beta-minus (β^-)	Electron (neutron $\rightarrow$ proton)	0	+1
Beta-plus (β^+)	Positron (proton $\rightarrow$ neutron)	0	-1
Electron capture	Absorbs an inner electron	0	-1
Gamma (γ)	High-energy photon	0	0

Penetrating power: $\alpha < \beta < \gamma$. Ionizing power runs the reverse. Fission splits heavy nuclei; fusion combines light nuclei; both release energy by moving toward the binding-energy peak near iron-56.

Thermodynamics (Physics View)

Concept	Formula / fact
Zeroth law	Objects in thermal equilibrium with a third object are in equilibrium with each other (basis of thermometers)
First law	$\Delta U = Q - W$ (W = work done BY the system)
Second law	Entropy of an isolated system never decreases; heat flows hot $\rightarrow$ cold spontaneously
Heat with temperature change	$q = mc\Delta T$ ($c_{\text{water}} = 1 \text{ cal/g}\cdot^\circ\text{C} = 4.184 \text{ J/g}\cdot^\circ\text{C}$)
Heat of phase change	$q = mL$ (temperature constant during phase change)
Thermal expansion	$\Delta L = \alpha L\Delta T$; $\Delta V = \beta V\Delta T$ ($\beta \approx 3\alpha$)
Pressure-volume work	$W = P\Delta V$ (constant P); area under P-V curve

HIGH-YIELD TIP

Watch the sign convention. Physics writes $\Delta U = Q - W$, where W is work done BY the system. Chemistry writes $\Delta U = q + w$, where w is work done ON the system. Same physics, opposite sign on work, so check which convention a passage uses.

Process	Constant	Key consequence
Isothermal	T	$\Delta U = 0$, so $Q = W$
Adiabatic	No heat exchange ($Q = 0$)	$\Delta U = -W$
Isobaric	P	$W = P\Delta V$
Isochoric (isovolumetric)	V	$W = 0$, so $\Delta U = Q$

Heat transfer: **conduction** (direct contact), **convection** (fluid movement), **radiation** (electromagnetic waves; no medium needed).

SECTION 3

General Chemistry

Atomic Structure

Quantum number	Symbol	Allowed values	Describes
Principal	n	1, 2, 3 ...	Shell / energy level and size
Azimuthal	l	0 to $n - 1$ ($s = 0$, $p = 1$, $d = 2$, $f = 3$)	Subshell shape
Magnetic	m_l	$-l$ to $+l$	Orbital orientation
Spin	m_s	$+\frac{1}{2}$ or $-\frac{1}{2}$	Electron spin

- **Aufbau:** fill lowest energy first ($n + l$ rule). **Hund:** fill degenerate orbitals singly with parallel spins first. **Pauli:** no two electrons share all four quantum numbers.
- Max electrons per subshell = $4l + 2$; per shell = $2n^2$.
- Exceptions: Cr = $[\text{Ar}]4s^13d^5$; Cu = $[\text{Ar}]4s^13d^{10}$ (half-filled and filled d subshells are stabilized). Transition metals lose 4s electrons before 3d.
- Isotopes differ in neutrons; atomic weight is the abundance-weighted average of isotope masses.

Periodic Trends

Every trend follows from **effective nuclear charge** ($Z_{\text{eff}} \approx Z - \text{shielding core electrons}$) and how far valence electrons sit from the nucleus.

- **Across a period:** each element adds a proton but no new shell. Same-shell electrons shield each other poorly, so Z_{eff} rises and valence electrons are pulled closer. Result: smaller radius, higher ionization energy, higher electronegativity, more favorable electron affinity.
- **Down a group:** each element adds a full shell. Valence electrons sit farther out behind more core electrons, so they are held less tightly. Result: larger radius, lower ionization energy, lower electronegativity.

Property	Across a period ($\rightarrow$)	Down a group ($\downarrow$)
Atomic radius	Decreases (greater effective nuclear charge)	Increases (more shells)
Ionization energy	Increases	Decreases
Electronegativity	Increases (F highest)	Decreases
Electron affinity (magnitude)	Increases	Decreases
Metallic character	Decreases	Increases

- **Ionization energy exceptions:** B < Be (boron's electron sits in a higher-energy 2p orbital) and O < N (oxygen's fourth p electron pairs up and is repelled). The same pattern repeats for groups 13 and 16 in later periods.
- **Successive ionization energies** jump sharply once the valence shell is empty (Na's second IE, Mg's third). The jump reveals the number of valence electrons.
- **Electron affinity exceptions:** noble gases and group 2 have little or no affinity (the electron must enter a new subshell); N is lower than C (half-filled p); Cl is more favorable than F (F is small and crowded).
- **Ion size:** cations are smaller than their neutral atoms; anions are larger. In an isoelectronic series, more protons means smaller: $\text{O}^{2-} > \text{F}^- > \text{Na}^+ > \text{Mg}^{2+}$.

Group	Chemical character
Alkali metals (1)	One valence electron; lose it easily to form +1 ions; react violently with water
Alkaline earth metals (2)	Form +2 ions; reactive, less so than group 1
Transition metals	Multiple oxidation states; colored complexes; often paramagnetic
Oxygen group / chalcogens (16)	Gain 2 electrons (−2); O and S are central to biological redox
Halogens (17)	Highly electronegative; gain one electron (−1); exist as diatomic molecules
Noble gases (18)	Full valence shells; very low reactivity; highest ionization energies in each period

Metals sit to the left and bottom; nonmetals to the upper right. Representative (main-group) elements are groups 1, 2, and 13–18.

Bonding and Molecular Geometry

- **Formal charge** = valence electrons – nonbonding electrons – $\frac{1}{2}(\text{bonding electrons})$. The best resonance structure minimizes formal charges and puts negative charge on the most electronegative atom.
- **Bond types:** nonpolar covalent ($\Delta EN < \text{about } 0.5$), polar covalent (about 0.5–1.7), ionic (> 1.7). Cutoffs vary slightly by textbook. Coordinate covalent bonds form when one atom donates both electrons (Lewis base → Lewis acid).
- Bond order $\uparrow \rightarrow$ bond length $\downarrow$ and bond strength $\uparrow$. Sigma bonds allow rotation; pi bonds do not, adding rigidity.

Electron domains	Hybridization	Electron geometry	Example molecular shapes (bond angle)
2	sp	Linear	Linear (180°): CO ₂
3	sp ²	Trigonal planar	Trigonal planar (120°): BF ₃ ; bent (<120°): SO ₂
4	sp ³	Tetrahedral	Tetrahedral (109.5°): CH ₄ ; trigonal pyramidal (107°): NH ₃ ; bent (104.5°): H ₂ O
5	sp ³ d	Trigonal bipyramidal	Seesaw: SF ₄ ; T-shaped: ClF ₃ ; linear: XeF ₂
6	sp ³ d ²	Octahedral	Octahedral (90°): SF ₆ ; square pyramidal; square planar: XeF ₄

Intermolecular Forces (strongest to weakest)

Ion–dipole > hydrogen bonding (H bonded to N, O, or F) > dipole–dipole > London dispersion. Stronger intermolecular forces raise boiling point, melting point, viscosity, and surface tension and lower vapor pressure. Dispersion forces grow with molecular size and surface area (straight chains boil higher than branched isomers).

Stoichiometry and Reaction Types

- Moles = mass / molar mass; percent composition = (mass of element / molar mass) $\times 100$.
- Empirical formula is the simplest whole-number ratio; molecular formula is a multiple of it.
- **Limiting reagent:** convert each reactant to moles of product; the smallest yield wins. Percent yield = actual/theoretical $\times 100$.
- **Oxidation state rules:** free elements = 0; O usually −2 (−1 in peroxides); H usually +1 (−1 in metal hydrides); F always −1; sum equals overall charge.

Type	General form	Example	How to spot it
Combination (synthesis)	$A + B \rightarrow AB$	$2H_2 + O_2 \rightarrow 2H_2O$	One product
Decomposition	$AB \rightarrow A + B$	$2H_2O_2 \rightarrow 2H_2O + O_2$	One reactant
Combustion	Fuel + $O_2 \rightarrow CO_2 + H_2O$	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	Hydrocarbon plus oxygen
Single displacement	$A + BC \rightarrow AC + B$	$Zn + CuSO_4 \rightarrow ZnSO_4 + Cu$	An element swaps into a compound; the more active metal wins
Double displacement (metathesis)	$AB + CD \rightarrow AD + CB$	$AgNO_3 + NaCl \rightarrow AgCl(s) + NaNO_3$	Partners swap; driven by a precipitate, gas, or water
Neutralization	Acid + base $\rightarrow$ salt + water	$HCl + NaOH \rightarrow NaCl + H_2O$	Special case of double displacement

Combustion and single displacement are always redox; combination and decomposition often are. Double displacement and neutralization are not (no oxidation states change).

Gases

Law	Formula	Notes
Ideal gas law	$PV = nRT$	STP = 273 K, 1 atm; 1 mol ideal gas = 22.4 L at STP
Combined gas law	$P_1V_1/T_1 = P_2V_2/T_2$	Boyle ($P \propto 1/V$), Charles ($V \propto T$), Gay-Lussac ($P \propto T$), Avogadro ($V \propto n$)
Dalton's law	$P_{\text{total}} = \sum P_i$; $P_i = X_i \cdot P_{\text{total}}$	Partial pressures
Graham's law	$r_1/r_2 = \sqrt{M_2/M_1}$	Lighter gases effuse faster
Kinetic energy	$KE_{\text{avg}} = (3/2)k_B \cdot T$	Depends only on temperature (k_B = Boltzmann constant)
RMS speed	$v_{\text{rms}} = \sqrt{3RT/M}$	M in kg/mol
Henry's law	$[A] = k_H \cdot P_A$	Gas solubility rises with partial pressure
Van der Waals equation	$(P + an^2/V^2)(V - nb) = nRT$	a corrects for attractions; b for molecular volume

- Real gases deviate most at **high pressure** (molecular volume matters; $V_{\text{real}} > V_{\text{ideal}}$) and **low temperature** (attractions matter; $P_{\text{real}} < P_{\text{ideal}}$).
- Heat capacity:** for gases, $C_p > C_v$ because at constant pressure some heat does expansion work ($C_p - C_v = R$ per mole of ideal gas).

Kinetics

Order	Rate law	Integrated form (linear plot)	Half-life	Units of k
Zero	rate = k	[A] vs t	$[A]_0/(2k)$	M/s
First	rate = k[A]	ln[A] vs t	$0.693/k$ (independent of [A])	s^{-1}
Second	rate = k[A] ²	1/[A] vs t	$1/(k[A]_0)$	$M^{-1}s^{-1}$

- Rate laws come from experiment (compare trials where one concentration changes), not from stoichiometric coefficients, unless the step is elementary.
- The slowest step (rate-determining step) controls the overall rate.
- Arrhenius: $k = Ae^{-E_a/RT}$. Higher T or lower $E_a \rightarrow$ faster rate.
- Catalysts lower activation energy for forward and reverse reactions equally; they do not change ΔG , ΔH , or K_{eq} .
- **Reading energy diagrams:** the peak is the transition state (activated complex); E_a is the climb from reactants to the peak; ΔH is products minus reactants; dips between peaks are intermediates; the tallest climb is the rate-determining step.
- Kinetic product forms faster (lower E_a); thermodynamic product is more stable (lower G).

Equilibrium

- For $aA + bB \rightleftharpoons cC + dD$: $K_{eq} = [C]^c[D]^d/([A]^a[B]^b)$. Exclude pure solids and liquids.
- $Q < K \rightarrow$ reaction proceeds forward; $Q > K \rightarrow$ reverse; $Q = K \rightarrow$ equilibrium.
- K changes only with temperature.
- Solubility: $K_{sp} = [M]^a[X]^{-b}$. If ion product $> K_{sp}$, precipitate forms. Common-ion effect lowers solubility.

Le Châtelier's principle, case by case

Use $N_2 + 3H_2 \rightleftharpoons 2NH_3$ ($\Delta H < 0$) as the running example. The system shifts to relieve whatever stress is applied.

Change	Shift	Does K change?	NH ₃ example
Add reactant or remove product	Forward	No	Removing NH ₃ drives more production
Add product or remove reactant	Reverse	No	Adding NH ₃ shifts left
Decrease volume (raise pressure)	Toward fewer moles of gas	No	Forward (4 mol gas $\rightarrow$ 2 mol)
Increase volume (lower pressure)	Toward more moles of gas	No	Reverse
Add inert gas at constant volume	No shift (partial pressures unchanged)	No	No change
Add inert gas at constant pressure	Toward more moles of gas (volume expands)	No	Reverse
Raise temperature	Toward the endothermic direction	Yes	Reverse; K decreases
Lower temperature	Toward the exothermic direction	Yes	Forward; K increases
Add a catalyst	No shift; equilibrium reached faster	No	No change in yield
Add a pure solid or liquid	No shift	No	No change

- Pressure changes do nothing when both sides have equal moles of gas.
- Treat heat as a product of exothermic reactions; temperature is the only change that alters K.
- **Biology version:** $CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$. Hyperventilation removes CO_2 , pulling the system left, lowering $[H^+]$ and raising blood pH. The common-ion effect is Le Châtelier applied to solubility.

Thermochemistry

Gibbs free energy (ΔG) is the energy available to do useful work. Its sign tells you the direction a reaction will go, never how fast.

- **$\Delta G = \Delta H - T\Delta S$:** a reaction is favored by releasing heat ($\Delta H < 0$) and increasing disorder ($\Delta S > 0$). When ΔH and ΔS have the same sign, the crossover temperature is $T = \Delta H/\Delta S$.
- **ΔG° vs ΔG :** ΔG° is at standard conditions (1 M, 1 atm, 298 K); biochemistry uses $\Delta G'^\circ$ at pH 7. Cells actually run at $\Delta G = \Delta G^\circ + RT \ln Q$.
- **At equilibrium, $\Delta G = 0$ and $Q = K$.** ΔG° is not zero at equilibrium; it is fixed by K through $\Delta G^\circ = -RT \ln K$.
- **Quick estimate:** at 298 K, each factor of 10 in K shifts ΔG° by about 5.7 kJ/mol. $K = 1000$ means $\Delta G^\circ \approx -17$ kJ/mol.
- **Spontaneous does not mean fast.** Diamond turning to graphite has $\Delta G < 0$ but takes geologic time; rate is set by activation energy, not ΔG .
- **Coupling:** ΔG values add. Glucose + $P_i \rightarrow$ glucose-6-phosphate ($\Delta G'^\circ = +13.8$ kJ/mol) becomes favorable when coupled to ATP hydrolysis (-30.5 kJ/mol): net -16.7 kJ/mol.

ΔG°	K	E°_{cell}	Direction at standard state
Negative	> 1	Positive	Products favored
Zero	$= 1$	Zero	Neither favored
Positive	< 1	Negative	Reactants favored

Concept	Formula / fact
Gibbs free energy	$\Delta G = \Delta H - T\Delta S$; $\Delta G < 0$ spontaneous
Standard free energy and K	$\Delta G^\circ = -RT \ln K$
Non-standard conditions	$\Delta G = \Delta G^\circ + RT \ln Q$
Hess's law	$\Delta H_{\text{rxn}} = \sum \Delta H_f(\text{products}) - \sum \Delta H_f(\text{reactants})$
Bond enthalpies	$\Delta H_{\text{rxn}} = \sum(\text{bonds broken}) - \sum(\text{bonds formed})$
State functions	P, V, T, H, S, G, U : path-independent. Heat and work are not.
Standard state	25 °C (298 K), 1 atm, 1 M; ΔH_f° of an element in its standard state = 0
Calorimetry	Coffee-cup (constant pressure) measures ΔH ; bomb calorimeter (constant volume) measures ΔU . $q = mc\Delta T$

ΔH	ΔS	Spontaneity
–	+	Always spontaneous
+	–	Never spontaneous
–	–	Spontaneous at low T
+	+	Spontaneous at high T

Phase diagrams: the triple point is where all three phases coexist; beyond the critical point, liquid and gas are indistinguishable (supercritical fluid). Water's solid-liquid line slopes negatively because ice is less dense than liquid water. Entropy: gas $>$ liquid $>$ solid.

Solutions

Concentration	Definition
Molarity (M)	mol solute / L solution
Molality (m)	mol solute / kg solvent (temperature independent)
Normality (N)	equivalents / L (e.g., 1 M H ₂ SO ₄ = 2 N in acid-base reactions)
Mole fraction (X)	mol component / total mol
Dilution	$M_1V_1 = M_2V_2$

Colligative property	Formula	Notes
Boiling point elevation	$\Delta T_b = iK_{bm}$	i = van't Hoff factor (NaCl $\approx$ 2, CaCl ₂ $\approx$ 3, glucose = 1)
Freezing point depression	$\Delta T_f = iK_{fm}$	
Osmotic pressure	$\Pi = iMRT$	Water moves toward higher solute concentration
Vapor pressure lowering (Raoult)	$P_A = X_A \cdot P_A^\circ$	Nonvolatile solutes lower vapor pressure

- **Complex ions:** a metal ion (Lewis acid) binds ligands (Lewis bases). Complex formation raises a salt's solubility: AgCl dissolves in aqueous NH₃ as Ag(NH₃)₂⁺ forms.
- **Solubility and pH:** salts with basic anions (OH⁻, CO₃²⁻, F⁻) dissolve better in acid, because H⁺ removes the anion from solution.

MNEMONIC

Always-soluble ions: Group 1 cations, NH₄⁺, NO₃⁻, and acetate. Most halides are soluble except with Ag⁺, Pb²⁺, and Hg₂²⁺.

Acids and Bases

Concept	Formula / fact
Definitions	Arrhenius: H ⁺ / OH ⁻ in water. Brønsted-Lowry: proton donor / acceptor. Lewis: electron-pair acceptor / donor
pH and pOH	$\text{pH} = -\log[\text{H}^+]$; $\text{pH} + \text{pOH} = 14$ at 25 °C
Water autoionization	$K_w = [\text{H}^+][\text{OH}^-] = 10^{-14}$ at 25 °C
Conjugate pairs	$K_a \times K_b = K_w$; $\text{p}K_a + \text{p}K_b = 14$
Weak acid pH	$[\text{H}^+] \approx \sqrt{K_a[\text{HA}]}$
Henderson-Hasselbalch	$\text{pH} = \text{p}K_a + \log([\text{A}^-]/[\text{HA}])$
Buffers	Best within $\text{p}K_a \pm 1$; maximum capacity at $\text{pH} = \text{p}K_a$

- Strong acids: HCl, HBr, HI, HNO₃, H₂SO₄, HClO₄ (and HClO₃). Strong bases: Group 1 hydroxides; Ca, Sr, Ba hydroxides.
- Stronger acid → weaker conjugate base. Acidity increases with electronegativity across a row and with atomic size down a group (HI > HF).
- **Salts:** the salt of a weak acid and strong base (sodium acetate) makes a basic solution; the salt of a weak base and strong acid (NH₄Cl) makes an acidic one.

- **Titration:** at the equivalence point, moles acid = moles base. Strong acid/strong base: pH 7. Weak acid/strong base: pH > 7. Weak base/strong acid: pH < 7. At the half-equivalence point, pH = pK_a.
- Choose an indicator whose pK_a is close to the equivalence-point pH. Polyprotic acids show multiple equivalence points.
- **Redox titration:** the endpoint is reached when electrons donated equal electrons accepted; KMnO₄ is self-indicating because its purple color persists past the endpoint.
- Amphoteric species (water, HCO₃⁻, amino acids) can act as acid or base.

Electrochemistry

Breaking a redox reaction into its parts

Split every redox reaction into an oxidation half and a reduction half, balance each, then make the electrons cancel.

1. Assign oxidation states; identify what is oxidized (number rises) and reduced (number falls).
2. Write the two half-reactions.
3. Balance atoms other than O and H.
4. Balance O by adding H₂O.
5. Balance H by adding H⁺.
6. Balance charge by adding electrons.
7. Multiply the halves so electrons lost equal electrons gained; add and cancel.
8. In basic solution, add OH⁻ to both sides to turn each H⁺ into H₂O, then cancel water.

WORKED EXAMPLE



Oxidation: $\text{Fe}^{2+} \rightarrow \text{Fe}^{3+} + \text{e}^-$ (Fe goes +2 → +3)

Reduction: $\text{MnO}_4^- + 8\text{H}^+ + 5\text{e}^- \rightarrow \text{Mn}^{2+} + 4\text{H}_2\text{O}$ (Mn goes +7 → +2)

Combine (oxidation × 5): $\text{MnO}_4^- + 8\text{H}^+ + 5\text{Fe}^{2+} \rightarrow \text{Mn}^{2+} + 5\text{Fe}^{3+} + 4\text{H}_2\text{O}$

Check charge: left = -1 + 8 + 10 = +17; right = +2 + 15 = +17. MnO₄⁻ is the oxidizing agent, Fe²⁺ the reducing agent, and n = 5 for ΔG = -nFE and the Nernst equation.

- **Disproportionation:** one species is both oxidized and reduced, as in $2\text{H}_2\text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{O}_2$ (O goes -1 to -2 and to 0).
- **Common oxidizing agents:** O₂, MnO₄⁻, Cr₂O₇²⁻, H₂O₂, halogens. **Common reducing agents:** active metals (Na, Zn), H₂, NaBH₄, LiAlH₄, NADH.
- **Biology version:** $\text{NAD}^+ + 2\text{e}^- + \text{H}^+ \rightarrow \text{NADH}$ is a reduction half-reaction; pairing NADH oxidation with O₂ reduction in the electron transport chain drives ATP synthesis.

Concept	Formula / fact
Redox basics	Oxidation = loss of electrons; reduction = gain. Reducing agent is oxidized; oxidizing agent is reduced
Cell potential	$E^\circ_{\text{cell}} = E^\circ_{\text{cathode}} - E^\circ_{\text{anode}}$ (using reduction potentials)
Free energy	$\Delta G^\circ = -nFE^\circ_{\text{cell}}$; positive E° → spontaneous
Nernst equation	$E = E^\circ - (0.0592/n) \log Q$ at 25 °C
Electrolysis (Faraday)	$\text{mol e}^- = \text{It/F}$; amount deposited at an electrode is proportional to charge passed

	Galvanic (voltaic) cell	Electrolytic cell
Spontaneous?	Yes ($\Delta G < 0$, $E > 0$)	No ($\Delta G > 0$, $E < 0$); needs external power
Anode	Oxidation; negative (–)	Oxidation; positive (+)
Cathode	Reduction; positive (+)	Reduction; negative (–)
Electron flow	Anode → cathode	Anode → cathode

- **Batteries:** lead-storage (Pb anode, PbO₂ cathode, H₂SO₄ electrolyte) and nickel-cadmium cells are rechargeable; recharging runs the cell in reverse as an electrolytic cell.

MNEMONIC

OIL RIG: Oxidation Is Loss, Reduction Is Gain. AN OX, RED CAT: anode = oxidation, cathode = reduction (true in every cell type). Concentration cells have $E^\circ = 0$ and generate voltage only from concentration differences (like the resting membrane potential).

SECTION 4

Organic Chemistry

Functional Groups and Naming Priority

When naming, the highest-priority group gets the suffix and the lowest possible number. Approximate priority (highest first):

Group	Structure	Suffix / prefix	Key features
Carboxylic acid	R-COOH	-oic acid / carboxy-	$pK_a \approx 4-5$; H-bond dimers, high bp
Anhydride	R-CO-O-CO-R	-oic anhydride	Very reactive acylating agent
Ester	R-COO-R'	-oate / alkoxycarbonyl-	Fruity smells; from acid + alcohol
Acyl halide	R-COX	-oyl halide	Most reactive acid derivative
Amide	R-CONR ₂	-amide / carbamoyl-	Least reactive derivative; resonance, planar
Nitrile	R-C $\equiv$ N	-nitrile / cyano-	Hydrolyzes to carboxylic acid
Aldehyde	R-CHO	-al / oxo-	More reactive than ketones
Ketone	R-CO-R'	-one / oxo-	α -hydrogens $pK_a \approx 20$
Alcohol	R-OH	-ol / hydroxy-	H-bonding; $pK_a \approx 16-18$
Thiol	R-SH	-thiol / sulfanyl-	More acidic than alcohols
Amine	R-NH ₂	-amine / amino-	Basic; pK_a of conjugate acid ≈ 10
Alkene / alkyne	C=C / C $\equiv$ C	-ene / -yne	Sites of addition reactions
Alkane, halide, ether	C-C, R-X, R-O-R	-ane / halo- / alkoxy-	Always named as substituents except alkane parent

Common names to recognize: formaldehyde (methanal), acetaldehyde (ethanal), acetone (propanone), formic acid (methanoic acid), acetic acid (ethanoic acid). Prefixes for carbon counts: meth-, eth-, prop-, but-, pent-, hex-, hept-, oct-, non-, dec-.

Isomerism and Stereochemistry

Term	Definition
Structural (constitutional) isomers	Same formula, different connectivity; different physical and chemical properties
Stereoisomers	Same connectivity, different spatial arrangement
Conformational isomers	Differ by rotation around σ bonds (staggered anti is most stable; eclipsed least). Cyclohexane chair: bulky groups prefer equatorial
Enantiomers	Non-superimposable mirror images; opposite configuration at every chiral center; identical physical properties except rotation of plane-polarized light
Diastereomers	Stereoisomers that are not mirror images; different physical properties; include cis/trans isomers

Term	Definition
Epimers	Diastereomers differing at exactly one chiral center (e.g., glucose and galactose at C4)
Anomers	Epimers at the new chiral center formed by ring closure (α vs β at C1 of glucose)
Meso compound	Has chiral centers but an internal plane of symmetry; optically inactive
Racemic mixture	50:50 enantiomers; no net optical rotation

- **Cahn-Ingold-Prelog:** rank substituents by atomic number. Point lowest priority away; 1→2→3 clockwise = R, counterclockwise = S. If lowest priority points toward you, reverse the answer.
- **E/Z:** highest-priority groups on the same side = Z (zusammen); opposite = E (entgegen).
- Maximum number of stereoisomers = 2^n (n = chiral centers).
- **Specific rotation:** $[\alpha] = \alpha_{\text{observed}} / (c \times l)$, c in g/mL, l in dm. (+) dextrorotatory vs (–) levorotatory is experimental and unrelated to R/S.
- **Enantiomeric excess** = $|\% \text{ major} - \% \text{ minor}| = \text{observed rotation} / \text{rotation of pure enantiomer} \times 100$.

Bonding in Organic Molecules

- **Resonance** delocalizes electrons over π systems, stabilizing charge. Conjugated systems (alternating single/double bonds) absorb UV-Vis light.
- **Aromaticity (Hückel):** cyclic, planar, fully conjugated, with $4n + 2$ π electrons. Antiaromatic: $4n$ π electrons (unstable).
- **Carbocation stability:** tertiary > secondary > primary > methyl (hyperconjugation and induction); allylic and benzylic cations are stabilized by resonance.
- Radical stability follows the same order. Carbanion stability is the reverse.
- **Biological aromatic heterocycles:** purines and pyrimidines (nucleic acid bases), imidazole (histidine), indole (tryptophan), and porphyrin (the ring that holds iron in heme).

Nucleophiles, Electrophiles, Leaving Groups

- **Nucleophiles** donate electron pairs (attack δ^+ carbons). Nucleophilicity rises with negative charge and lower electronegativity. In polar protic solvents, larger atoms are better nucleophiles ($I^- > Br^- > Cl^- > F^-$); in polar aprotic solvents, basicity trends apply (F^- best).
- **Electrophiles** accept electron pairs: carbonyl carbons, carbocations, alkyl halides.
- **Good leaving groups** are weak bases (conjugate bases of strong acids): $I^- > Br^- > Cl^- > F^-$; tosylates and mesylates are excellent. $-OH$ is poor unless protonated to water.

Substitution and Elimination

	SN1	SN2	E1	E2
Mechanism	Two steps via carbocation	One concerted step, backside attack	Two steps via carbocation	One concerted step, anti-periplanar H
Rate law	$k[\text{substrate}]$	$k[\text{substrate}][\text{Nu}]$	$k[\text{substrate}]$	$k[\text{substrate}][\text{base}]$
Substrate	$3^\circ > 2^\circ$ (never methyl/ 1°)	Methyl $> 1^\circ > 2^\circ$ (never 3°)	$3^\circ > 2^\circ$	$3^\circ > 2^\circ > 1^\circ$
Reagent	Weak nucleophile	Strong nucleophile	Weak base	Strong, often bulky, base
Solvent	Polar protic	Polar aprotic	Polar protic	Varies

	SN1	SN2	E1	E2
Stereochemistry	Racemization (possible rearrangement)	Inversion of configuration	Zaitsev (more substituted alkene)	Zaitsev; bulky bases give Hofmann (less substituted)

HIGH-YIELD TIP

Heat favors elimination over substitution. Polar aprotic solvents (DMSO, DMF, acetone, acetonitrile) don't cage nucleophiles with hydrogen bonds, so they speed up SN2.

Oxidation and Reduction

Reagent	Type	Effect
PCC	Mild oxidant	1° alcohol → aldehyde (stops there); 2° → ketone
CrO₃/H₂SO₄ (Jones), Na₂Cr₂O₇, KMnO₄	Strong oxidants	1° alcohol → carboxylic acid; 2° → ketone; 3° no reaction
LiAlH₄	Strong reductant	Reduces aldehydes, ketones, esters, carboxylic acids, amides
NaBH₄	Mild reductant	Reduces aldehydes and ketones only
H₂ + Pd/Pt/Ni	Catalytic hydrogenation	Alkenes/alkynes → alkanes (syn addition)

In organic chemistry, oxidation usually means more bonds to O (or fewer to H); reduction means more bonds to H.

Aldehydes and Ketones

- **Nucleophilic addition:** the carbonyl carbon is electrophilic. Aldehydes react faster than ketones (less steric hindrance, less electron donation).
- **Hydration:** + H₂O → geminal diol. **Cyanohydrin:** + HCN.
- **Alcohols:** + 1 ROH → hemiacetal/hemiketal; + 2 ROH (acid) → acetal/ketal (a common protecting group).
- **Amines:** + 1° amine → imine (Schiff base, C=N); + 2° amine → enamine.
- **Keto-enol tautomerism:** keto form usually predominates. α-hydrogens are acidic (pK_a ≈ 20) because the enolate is resonance-stabilized; tautomerism also racemizes α-carbons.
- **Aldol reaction:** an enolate (nucleophile) attacks another carbonyl → β-hydroxy carbonyl; with heat, dehydration gives an α,β-unsaturated carbonyl (aldol condensation). Retro-aldol reverses it.
- **Kinetic enolate:** less substituted, formed with bulky base (LDA), low temperature. **Thermodynamic enolate:** more substituted, higher temperature.

Carboxylic Acids and Derivatives

Reactivity toward nucleophilic acyl substitution: **acyl halide > anhydride > ester ≈ carboxylic acid > amide**. A more reactive derivative can be converted into a less reactive one, not the reverse (without extra steps).

Reaction	Reactants → products
Fischer esterification	Carboxylic acid + alcohol (acid catalyst) → ester + water
Saponification	Ester (fat) + NaOH → carboxylate salt (soap) + alcohol (glycerol)

Reaction	Reactants → products
Transesterification	Ester + different alcohol → new ester
Amide formation	Acyl derivative + amine → amide (peptide bonds); cyclic amides are lactams, cyclic esters are lactones
Hydrolysis	Any derivative + water → carboxylic acid (amides need strong acid/base and heat)
Reduction	LiAlH_4 reduces carboxylic acids all the way to 1° alcohols
Decarboxylation	β -keto acids lose CO_2 on heating via a cyclic transition state
α-substitution	The α (2-) carbon can be deprotonated and substituted (e.g., α -halogenation), just like ketones

- Carboxylic acid acidity increases with nearby electron-withdrawing groups (e.g., trichloroacetic > acetic).
- β -lactams are strained cyclic amides and therefore unusually reactive (basis of penicillin's action). Steric bulk slows nucleophilic attack; electron-withdrawing groups speed it.
- Soaps form micelles: nonpolar tails inward, charged heads outward.

Other Nitrogen, Oxygen and Phosphorus Chemistry

- **Strecker synthesis:** aldehyde + NH_3 + HCN → aminonitrile → hydrolysis → racemic amino acid.
- **Gabriel synthesis:** phthalimide + diethyl bromomalonate → alkylation → hydrolysis/decarboxylation → racemic amino acid.
- **Phenols** are more acidic than alcohols (resonance-stabilized phenoxide). Quinones are oxidized phenols; hydroquinone/quinone pairs such as ubiquinone act as biological two-electron redox centers in the ETC.
- **Protecting groups:** acetals protect carbonyls; t-butyl ethers and silyl ethers protect alcohols. Converting $-\text{OH}$ to a mesylate or tosylate turns a poor leaving group into an excellent one.
- **Phosphoric acid:** three pK_a values; phosphoanhydride bonds (ATP) release energy on hydrolysis due to charge repulsion relief and resonance stabilization of products.

Spectroscopy

Infrared (IR): identifies functional groups

Bond	Wavenumber (cm^{-1})	Appearance
O-H (alcohol)	3200-3600	Broad, strong
O-H (carboxylic acid)	2500-3300	Very broad, overlaps C-H
N-H	3300-3500	Sharp; 1° amines show two peaks
C-H (sp^3 / sp^2 / sp)	<3000 / >3000 / $\approx$ 3300	Sharp
$\text{C}\equiv\text{C}$, $\text{C}\equiv\text{N}$	2100-2260	Sharp
$\text{C}=\text{O}$	1650-1750 ($\approx$ 1700)	Strong, sharp
$\text{C}=\text{C}$	1600-1680	Weak to medium

The region below about 1500 cm^{-1} is the **fingerprint region**: unique to each molecule but rarely interpreted peak by peak.

¹H NMR: identifies hydrogen environments

Environment	Chemical shift (ppm)
Alkyl C-H	0.9-1.5
Allylic / α to carbonyl	1.7-2.6
C-H next to O or halogen (alcohols, ethers, esters)	3.3-4.5
Vinyl C-H	4.5-6.5
Aromatic C-H	6.5-8.0
Aldehyde C-H	9-10
Carboxylic acid O-H	10.5-12

- Number of peaks = number of distinct H environments; integration = relative number of H.
- Splitting: $n + 1$ rule (n = neighboring, non-equivalent H). Doublet = 1 neighbor, triplet = 2, quartet = 3.
- Electron-withdrawing groups deshield protons → downfield (higher ppm). TMS reference = 0 ppm.
- **UV-Vis:** detects conjugated π systems and nonbonding-electron transitions; more conjugation → longer λ_{max} .
- **Visible absorption:** a substance appears the complementary color of what it absorbs (carotene absorbs blue and looks orange). Acid-base indicators change color because protonation changes their conjugation.
- **Mass spectrometry:** gives molecular weight (M^+ peak) and fragmentation; Cl and Br show characteristic $M+2$ isotope peaks.

Separation and Purification

Technique	Separates by	Key points
Liquid-liquid extraction	Solubility / acid-base chemistry	Acids pulled into aqueous base (as salts); bases into aqueous acid
Simple distillation	Boiling point	Works when bp differs by $> 25^\circ\text{C}$
Fractional distillation	Boiling point	For close boiling points; fractionating column
Vacuum distillation	Boiling point at reduced pressure	For high-bp or heat-sensitive compounds
Recrystallization	Solubility vs temperature	Solvent dissolves compound when hot, not when cold
Thin-layer / column chromatography	Polarity	Polar silica stationary phase: nonpolar compounds travel farther (higher R_f = distance compound / distance solvent)
Reverse-phase chromatography	Polarity	Nonpolar stationary phase: polar compounds elute first
Gas chromatography	Volatility	Vaporized sample; often paired with mass spec
Size-exclusion	Size	Large molecules elute first (can't enter pores)
Ion-exchange	Charge	Cation exchange beads are negative and bind positive proteins
Affinity	Specific binding	Ligand/antibody column; elute with free ligand or salt
Resolving enantiomers	Chirality	React a racemate with a pure chiral agent to make separable diastereomers

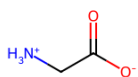
SECTION 5

Biochemistry

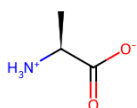
The 20 Amino Acids

All except glycine are chiral; proteinogenic amino acids are L (S configuration, except cysteine, which is R). Isoleucine and threonine each have a second chiral center. Backbone pK_a values: α -COOH $\approx$ 2, α -NH₃⁺ $\approx$ 9–10.

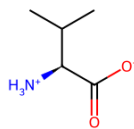
Name	3 / 1 letter	Class	Side chain (R)	Notes (side-chain pK_a where relevant)
Glycine	Gly / G	Nonpolar	-H	Achiral; flexible
Alanine	Ala / A	Nonpolar	-CH ₃	
Valine	Val / V	Nonpolar	-CH(CH ₃) ₂	Branched-chain
Leucine	Leu / L	Nonpolar	-CH ₂ CH(CH ₃) ₂	Branched-chain; purely ketogenic (with lysine)
Isoleucine	Ile / I	Nonpolar	-CH(CH ₃)CH ₂ CH ₃	Branched-chain; two chiral centers
Methionine	Met / M	Nonpolar	-CH ₂ CH ₂ SCH ₃	Thioether; start codon AUG
Proline	Pro / P	Nonpolar	Ring back to backbone N	Cyclic; kinks and breaks α -helices
Phenylalanine	Phe / F	Aromatic, nonpolar	-CH ₂ -phenyl	
Tryptophan	Trp / W	Aromatic	-CH ₂ -indole	Absorbs at 280 nm
Tyrosine	Tyr / Y	Aromatic, polar	-CH ₂ -phenyl-OH	Phenol -OH ($\approx$ 10); phosphorylation site
Serine	Ser / S	Polar	-CH ₂ OH	Phosphorylation site
Threonine	Thr / T	Polar	-CH(OH)CH ₃	Two chiral centers; phosphorylation site
Cysteine	Cys / C	Polar	-CH ₂ SH	Thiol ($\approx$ 8.3); forms disulfide bonds (cystine)
Asparagine	Asn / N	Polar	-CH ₂ CONH ₂	Amide; N-linked glycosylation
Glutamine	Gln / Q	Polar	-CH ₂ CH ₂ CONH ₂	Amide; nitrogen carrier
Aspartate	Asp / D	Acidic (-)	-CH ₂ COO ⁻	$\approx$ 3.9
Glutamate	Glu / E	Acidic (-)	-CH ₂ CH ₂ COO ⁻	$\approx$ 4.2
Lysine	Lys / K	Basic (+)	-(CH ₂) ₄ NH ₃ ⁺	$\approx$ 10.5
Arginine	Arg / R	Basic (+)	-(CH ₂) ₃ NH-C(=NH ₂ ⁺)NH ₂	$\approx$ 12.5; guanidinium group
Histidine	His / H	Basic (+/neutral)	-CH ₂ -imidazole	$\approx$ 6.0; imidazole buffers near physiological pH



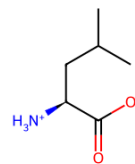
Glycine (Gly, G) | Nonpolar



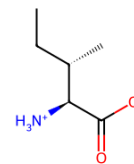
Alanine (Ala, A) | Nonpolar



Valine (Val, V) | Nonpolar



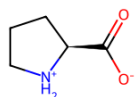
Leucine (Leu, L) | Nonpolar



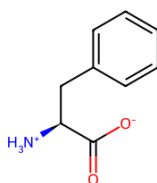
Isoleucine (Ile, I) | Nonpolar



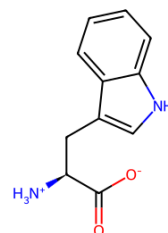
Methionine (Met, M) | Nonpolar



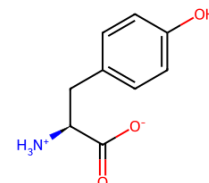
Proline (Pro, P) | Nonpolar



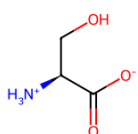
Phenylalanine (Phe, F) | Aromatic



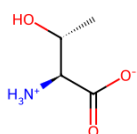
Tryptophan (Trp, W) | Aromatic



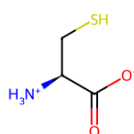
Tyrosine (Tyr, Y) | Aromatic



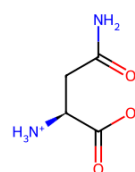
Serine (Ser, S) | Polar



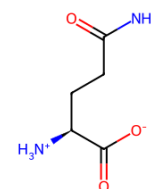
Threonine (Thr, T) | Polar



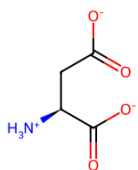
Cysteine (Cys, C) | Polar



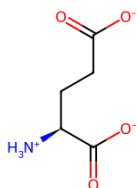
Asparagine (Asn, N) | Polar



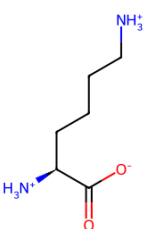
Glutamine (Gln, Q) | Polar



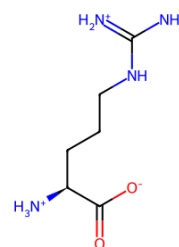
Aspartate (Asp, D) | Acidic



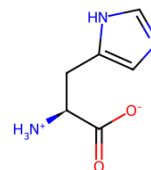
Glutamate (Glu, E) | Acidic



Lysine (Lys, K) | Basic



Arginine (Arg, R) | Basic



Histidine (His, H) | Basic

All 20 L-amino acids drawn as they exist at physiological pH (zwitterions), backbone at the bottom, side chain on top.

MNEMONIC

Learn structures by pattern, not by rote. Ala + branching = Val; Val + one CH₂ = Leu or Ile (Leu branches one carbon later). Ser + CH₃ = Thr; Phe + OH = Tyr; Ser with S in place of O = Cys. Asp/Asn and Glu/Gln are acid/amide pairs, and Glu and Gln are one CH₂ longer ("E is longer than D"). Lys ends in an amine, Arg in a guanidinium, His in an imidazole ring.

- **Isoelectric point (pI):** average the two pK_a values that surround the neutral (zwitterion) form. Neutral amino acids: pI ≈ 6. Acidic: pI ≈ 3. Basic: pI ≈ 10.
- At pH < pI the molecule is net positive; at pH > pI, net negative. In isoelectric focusing, proteins stop migrating at their pI.
- Peptide bonds are planar and rigid (partial double-bond character), formed by condensation (dehydration) and broken by hydrolysis.

Protein Structure

Level	Defined by	Stabilized by
Primary	Amino acid sequence	Covalent peptide bonds
Secondary	α -helices, β -pleated sheets	Backbone hydrogen bonds
Tertiary	3-D fold of one chain	Hydrophobic effect, disulfide bonds, salt bridges, H-bonds, van der Waals
Quaternary	Arrangement of multiple subunits	Same interactions as tertiary (e.g., hemoglobin's 4 subunits)

- The **hydrophobic effect** (increase in water's entropy when nonpolar groups cluster and the solvation layer is released) is the main driver of folding.
- **Denaturation** by heat, pH extremes, detergents, urea, or salts disrupts noncovalent structure; primary structure stays intact.
- Chaperones assist folding. Prions are misfolded proteins that induce misfolding in normal copies (β -sheet rich).
- Protein types: structural (collagen, elastin, keratin, actin, tubulin), motor (myosin, kinesin, dynein), binding (antibodies, CAMs), enzymes, channels and pumps.
- **Quantifying protein:** Beer-Lambert law $A = \epsilon bc$; protein concentration is measured by absorbance at 280 nm or the Bradford assay.

Enzymes

Class	Reaction catalyzed
Ligase	Joins two molecules using ATP
Oxidoreductase	Redox reactions (dehydrogenases, oxidases)
Transferase	Moves a functional group (kinases transfer phosphate)
Hydrolase	Cleaves bonds using water (proteases, lipases, phosphatases)
Isomerase	Rearranges bonds within a molecule
Lyase	Cleaves or forms bonds without water or redox (synthases)

MNEMONIC

LOTHIL: Ligase, Oxidoreductase, Transferase, Hydrolase, Isomerase, Lyase.

- Enzymes lower E_a by stabilizing the transition state; they don't change ΔG or K_{eq} and aren't consumed.
- **Induced-fit model:** the active site changes shape on substrate binding (more accurate than lock-and-key).
- **Cofactors:** metal ions or small organics. **Coenzymes:** organic cofactors, often from water-soluble vitamins (NAD⁺ from niacin B3, FAD from riboflavin B2, CoA from pantothenic acid B5, TPP from thiamine B1).
- Activity depends on local conditions: each enzyme has an optimal temperature and pH (pepsin ≈ 2 , most enzymes ≈ 7.4).
- **Regulation:** allosteric effectors, covalent modification (phosphorylation), zymogens (inactive precursors like trypsinogen, pepsinogen), feedback inhibition.

Michaelis-Menten Kinetics

Equation / term	Meaning
$v = V_{\max} [S] / (K_m + [S])$	Initial velocity as a function of substrate
K_m	$[S]$ at which $v = \frac{1}{2}V_{\max}$; lower K_m = higher affinity
$k_{\text{cat}} = V_{\max} / [E]_{\text{total}}$	Turnover number (substrate molecules per enzyme per second)
k_{cat} / K_m	Catalytic efficiency
Lineweaver-Burk: $1/v = (K_m/V_{\max})(1/[S]) + 1/V_{\max}$	y-intercept = $1/V_{\max}$; x-intercept = $-1/K_m$; slope = $K_m/V_{\max}$
Cooperativity (Hill coefficient n)	$n > 1$ positive (sigmoidal curve, e.g., hemoglobin); $n < 1$ negative; $n = 1$ none

Inhibition	Binds	K_m	$V_{\max}$	Lineweaver-Burk
Competitive	Active site (free enzyme)	↑	No change	Lines cross at y-axis
Noncompetitive	Allosteric site, E and ES equally	No change	↓	Lines cross at x-axis
Mixed	Allosteric site, E and ES unequally	↑ or ↓	↓	Lines cross off-axis
Uncompetitive	ES complex only	↓	↓	Parallel lines

HIGH-YIELD TIP

Competitive inhibition can be overcome by adding more substrate; the others cannot. Irreversible inhibitors (e.g., aspirin acetylating COX) permanently inactivate enzymes.

Carbohydrates

- Aldoses have an aldehyde; ketoses a ketone. Trioses (3C) through hexoses (6C). D/L is assigned by the chiral carbon farthest from the carbonyl (OH on right in Fischer projection = D).
- In cyclization, the C5 -OH attacks the carbonyl, forming a hemiacetal. α anomer: C1 -OH trans to CH_2OH (axial, down in Haworth); β : cis (equatorial, up). Mutarotation interconverts them.
- Reducing sugars have a free hemiacetal (detected by Tollens' and Benedict's reagents).
- Disaccharides:** sucrose (glucose $\alpha 1 \rightarrow \beta 2$ fructose, non-reducing), lactose (galactose $\beta 1 \rightarrow 4$ glucose), maltose (glucose $\alpha 1 \rightarrow 4$ glucose).
- Polysaccharides:** starch (amylose $\alpha 1 \rightarrow 4$; amylopectin adds $\alpha 1 \rightarrow 6$ branches), glycogen (more branched), cellulose ($\beta 1 \rightarrow 4$; humans can't digest).

Lipids

Type	Structure / role
Fatty acids	Carboxylic acid + hydrocarbon tail. Saturated (no C=C; solid, pack tightly) vs unsaturated (cis kinks; liquid, increase membrane fluidity)
Triacylglycerols	Glycerol + 3 fatty acids; energy storage in adipocytes (9 kcal/g)
Glycerophospholipids	Glycerol + 2 fatty acids + phosphate head group; main membrane lipid
Sphingolipids	Sphingosine backbone: sphingomyelin (myelin), glycosphingolipids (cerebrosides, gangliosides)
Waxes	Long-chain fatty acid + long-chain alcohol; waterproofing and protection

Type	Structure / role
Steroids	Four fused rings: cholesterol (membrane fluidity buffer; precursor to steroid hormones, bile acids, vitamin D)
Terpenes	Built from isoprene (5C) units; precursors of steroids and vitamin A
Eicosanoids	Prostaglandins, thromboxanes, leukotrienes from arachidonic acid; inflammation and signaling
Fat-soluble vitamins	A (vision), D (Ca^{2+} absorption), E (antioxidant), K (clotting factors)

Nucleic Acids

- Nucleoside = sugar + base; nucleotide = nucleoside + phosphate(s).
- Purines (two rings): adenine, guanine. Pyrimidines (one ring): cytosine, thymine (DNA), uracil (RNA).
- A=T (2 hydrogen bonds), G≡C (3 hydrogen bonds). Higher GC content → higher melting temperature.
- DNA is antiparallel, read and synthesized 5'→3'; Watson-Crick B-DNA is a right-handed double helix. Chargaff's rules: %A = %T, %G = %C.
- RNA has a 2' -OH on ribose (less stable, more reactive than DNA).

MNEMONIC

CUT the PYe: Cytosine, Uracil, Thymine are PYrimidines. Pure As Gold: Purines are Adenine and Guanine.

Bioenergetics and Metabolism Overview

- ATP hydrolysis: $\Delta G^\circ \approx -30.5 \text{ kJ/mol}$. Cells couple unfavorable reactions to ATP hydrolysis (see Gibbs free energy, Section 3).
- NADH, FADH_2 , and NADPH are electron carriers (flavoproteins carry FAD/FMN). NADH/ FADH_2 feed the ETC (catabolism); NADPH powers biosynthesis and antioxidant defense (anabolism).
- Energy yields: carbohydrates and protein $\approx 4 \text{ kcal/g}$; fat $\approx 9 \text{ kcal/g}$; ethanol $\approx 7 \text{ kcal/g}$.
- Fed state:** insulin dominates (storage). **Fasting:** glucagon, epinephrine, cortisol dominate (mobilization). **Starvation:** ketone bodies supply the brain.

Glucose Metabolism

Pathway	Location	Key / rate-limiting enzyme	Net products and notes
Glycolysis	Cytoplasm	PFK-1 (activated by AMP, F-2,6-BP; inhibited by ATP, citrate). Other irreversible steps: hexokinase/glucokinase, pyruvate kinase	Glucose → 2 pyruvate + 2 ATP (net) + 2 NADH. Substrate-level phosphorylation by phosphoglycerate kinase and pyruvate kinase
Fermentation	Cytoplasm	Lactate dehydrogenase	Regenerates NAD^+ when O_2 is lacking; pyruvate → lactate (humans) or ethanol (yeast)
Pyruvate dehydrogenase (PDH)	Mitochondrial matrix	PDH complex (needs TPP, lipoic acid, CoA, FAD, NAD^+)	Pyruvate → acetyl-CoA + CO_2 + NADH; irreversible

Pathway	Location	Key / rate-limiting enzyme	Net products and notes
Citric acid (Krebs/TCA) cycle	Mitochondrial matrix	Isocitrate dehydrogenase; also citrate synthase and α -ketoglutarate dehydrogenase. Inhibited by ATP and NADH; activated by ADP and Ca^{2+}	Per acetyl-CoA: 3 NADH, 1 FADH ₂ , 1 GTP, 2 CO ₂
Gluconeogenesis	Mostly liver (cytoplasm + mitochondria)	Fructose-1,6-bisphosphatase; bypass enzymes: pyruvate carboxylase, PEPCK, F-1,6-BPase, glucose-6-phosphatase	Makes glucose from lactate, glycerol, glucogenic amino acids (not even-chain fatty acids)
Glycogenesis / glycogenolysis	Liver and muscle	Glycogen synthase (activated by insulin) / glycogen phosphorylase (activated by glucagon, epinephrine, AMP in muscle)	Muscle lacks glucose-6-phosphatase, so it uses its glycogen only for itself
Pentose phosphate pathway	Cytoplasm	Glucose-6-phosphate dehydrogenase	NADPH + ribose-5-phosphate (nucleotide synthesis)

MNEMONIC

Citric acid cycle intermediates: "Please Can I Keep Selling Seashells For Money, Officer?" Pyruvate ($\rightarrow$ acetyl-CoA), Citrate, Isocitrate, α -Ketoglutarate, Succinyl-CoA, Succinate, Fumarate, Malate, Oxaloacetate.

Oxidative Phosphorylation

Component	Function
Complex I (NADH dehydrogenase)	Accepts electrons from NADH; pumps H ⁺
Complex II (succinate dehydrogenase)	Accepts electrons from FADH ₂ ; also a TCA enzyme; pumps no H ⁺
Coenzyme Q (ubiquinone)	Mobile carrier to Complex III
Complex III (cytochrome bc₁)	Pumps H ⁺ ; passes electrons to cytochrome c
Complex IV (cytochrome c oxidase)	Reduces O ₂ (final electron acceptor) to H ₂ O; pumps H ⁺
ATP synthase (Complex V)	H ⁺ flows back into matrix through F ₀ ; F ₁ makes ATP (chemiosmotic coupling, driven by the proton-motive force)

- ≈ 2.5 ATP per NADH, ≈ 1.5 ATP per FADH₂; ≈ 30 – 32 ATP per glucose total.
- Cytoplasmic NADH enters via the glycerol-3-phosphate shuttle ($\rightarrow$ FADH₂, fewer ATP) or malate-aspartate shuttle.
- Uncouplers (e.g., thermogenin in brown fat, DNP) dissipate the gradient as heat. Cyanide and CO block Complex IV; oligomycin blocks ATP synthase. Oxidative phosphorylation speeds up when ADP is plentiful (respiratory control).
- **Mitochondria, apoptosis, and oxidative stress:** leaked electrons form reactive oxygen species that damage lipids, proteins, and DNA; mitochondria release cytochrome c to trigger apoptosis.

Lipid and Protein Metabolism

Process	Location	Key facts
Digestion and transport of fats	Small intestine $\rightarrow$ lymph $\rightarrow$ blood	Bile salts emulsify; lipases release fatty acids; packaged as chylomicrons; hormone-sensitive lipase mobilizes stored fat

Process	Location	Key facts
Fatty acid synthesis	Cytoplasm (liver)	Rate-limiting: acetyl-CoA carboxylase (makes malonyl-CoA); uses NADPH; citrate shuttles acetyl-CoA out of mitochondria; product is palmitate (16:0)
β-oxidation	Mitochondria	Carnitine shuttle (carnitine acyltransferase I is inhibited by malonyl-CoA); each cycle yields 1 NADH, 1 FADH ₂ , 1 acetyl-CoA. Unsaturated fats need extra isomerase/reductase steps and yield slightly less energy
Ketogenesis	Liver mitochondria	Acetyl-CoA $\rightarrow$ acetoacetate, β -hydroxybutyrate (fasting, uncontrolled diabetes); liver cannot use ketones
Cholesterol synthesis	Cytoplasm / smooth ER	Rate-limiting: HMG-CoA reductase (target of statins)
Lipoproteins	Blood	Chylomicrons (dietary fat), VLDL (liver-made TAG), LDL (delivers cholesterol), HDL (reverse cholesterol transport)
Protein catabolism	Liver	Transamination removes amino groups; ammonia $\rightarrow$ urea via the urea cycle (mitochondria + cytoplasm)

Hormonal Regulation and Integration of Metabolism

Hormone	Metabolic effects
Insulin	$\uparrow$ glucose uptake (GLUT4 in muscle, adipose), glycogenesis, fat and protein synthesis; $\downarrow$ gluconeogenesis, lipolysis
Glucagon	$\uparrow$ glycogenolysis, gluconeogenesis, ketogenesis in liver
Cortisol	$\uparrow$ gluconeogenesis, protein breakdown, lipolysis; long-term stress response
Epinephrine / norepinephrine	$\uparrow$ glycogenolysis and lipolysis; rapid fight-or-flight
Thyroid hormones (T₃/T₄)	$\uparrow$ basal metabolic rate, O ₂ consumption, heat production

Tissue-specific metabolism

Tissue	Fed state	Fasting state	Key constraint
Liver	Makes glycogen and fatty acids	Glycogenolysis, gluconeogenesis, ketogenesis	Cannot use ketone bodies
Skeletal muscle	Takes up glucose (insulin-driven GLUT4), stores glycogen	Burns fatty acids, later ketones	No glucose-6-phosphatase
Cardiac muscle	Mostly fatty acids	Fatty acids, ketones, lactate	Highly aerobic; little glycogen
Adipose tissue	Stores triacylglycerols	Lipolysis releases fatty acids and glycerol	Glycerol feeds liver gluconeogenesis
Brain	Glucose only	Glucose, then ketones in prolonged starvation	Cannot use fatty acids
Red blood cells	Glucose only	Glucose only	No mitochondria; anaerobic glycolysis

Obesity and regulation of body mass: leptin from adipose tissue signals satiety (obesity often involves leptin resistance); ghrelin from the stomach signals hunger; insulin promotes storage. Weight changes when energy intake and expenditure are unbalanced, and the hypothalamus defends a body-weight set point.

SECTION 6

Molecular Biology and Lab Techniques

The Central Dogma

Genetic information flows **DNA → RNA → protein**. The exceptions are what the MCAT likes to test.

Process	Template → product	Enzyme	Synthesis direction	Eukaryotes	Prokaryotes
Replication	DNA → DNA	DNA polymerase	5'→3'	Nucleus (and mitochondria)	Cytoplasm (nucleoid)
Transcription	DNA template strand (read 3'→5') → RNA	RNA polymerase	5'→3'	Nucleus	Cytoplasm
Translation	mRNA (read 5'→3') → polypeptide	Ribosome (rRNA peptidyl transferase)	N-terminus → C-terminus	Cytoplasm, rough ER	Cytoplasm, coupled to transcription
Reverse transcription	RNA → DNA	Reverse transcriptase	5'→3'	Retroviruses; telomerase	
RNA replication	RNA → RNA	RNA-dependent RNA polymerase	5'→3'	RNA viruses	

- The mRNA matches the **coding (sense) strand**, with U in place of T, and is complementary and antiparallel to the **template (antisense) strand**.
- Prions break the dogma differently: a misfolded protein templates misfolding of normal protein, with no nucleic acid involved.

WORKED EXAMPLE

Template 3'-TAC GGA-5' → mRNA 5'-AUG CCU-3' → Met-Pro. The tRNA anticodon that reads AUG is 3'-UAC-5'.

DNA Structure and Chromosome Organization

- **Nucleosomes:** DNA (negative) wraps around positively charged histone octamers (two each of H2A, H2B, H3, H4; rich in Lys and Arg). H1 links nucleosomes into compact fibers.
- **Supercoiling** builds up ahead of replication and transcription; topoisomerases relieve it.
- **Heterochromatin:** condensed, transcriptionally silent. **Euchromatin:** open, active.
- **Centromeres** join sister chromatids and anchor kinetochores; **telomeres** are TTAGGG repeats that cap chromosome ends and shorten with each division unless telomerase extends them.
- **Single-copy vs repetitive DNA:** most genes are single-copy; repetitive DNA includes satellite DNA at centromeres and telomeres plus transposable elements.
- **Denaturation, reannealing, hybridization:** heat or high pH separates strands; cooling lets complementary strands reanneal. GC-rich DNA melts at higher temperature. Hybridization of a labeled probe to its complement underlies blots, microarrays, and PCR primer binding.

DNA Replication

Enzyme / protein	Role
Helicase	Unwinds the double helix at the replication fork
Single-strand binding proteins	Keep strands apart
Topoisomerases (DNA gyrase in prokaryotes)	Relieve supercoiling ahead of the fork
Primase	Lays down RNA primers
DNA polymerase III (prok.) / α, δ, ϵ (euk.)	Synthesizes DNA 5'→3'; proofreads 3'→5'
DNA polymerase I (prok.) / RNase H (euk.)	Removes RNA primers and fills gaps
DNA ligase	Seals nicks between Okazaki fragments
Telomerase	Extends telomeres (repetitive ends) in germ, stem, and cancer cells

- Replication is **semiconservative** (Meselson–Stahl). Leading strand: continuous. Lagging strand: discontinuous Okazaki fragments.
- Prokaryotes: one origin, circular chromosome. Eukaryotes: many origins, linear chromosomes.
- **Repair:** proofreading during replication; mismatch repair (after replication; MSH2/MLH1); nucleotide excision (bulky lesions like thymine dimers from UV); base excision (single damaged bases).

Transcription and RNA Processing

- RNA polymerase reads the template (antisense) strand 3'→5' and builds RNA 5'→3'; the RNA matches the coding (sense) strand (with U for T). No primer needed.
- Eukaryotic RNA polymerases: I (rRNA), II (mRNA; binds TATA box with transcription factors), III (tRNA, 5S rRNA).
- **Processing** (eukaryotes, in nucleus): 5' 7-methylguanosine cap, 3' poly-A tail, splicing out introns by the spliceosome (snRNPs with snRNAs, a ribozyme). Alternative splicing produces multiple proteins from one gene.
- **Why introns matter:** they enable alternative splicing and exon shuffling, which speeds the evolution of new proteins.
- Prokaryotes transcribe and translate simultaneously in the cytoplasm; mRNA is often polycistronic.

The Genetic Code and Translation

- Codons are triplets read 5'→3'. Start codon: AUG (methionine; N-formylmethionine in prokaryotes). Stop codons: UAA, UAG, UGA.
- The code is **degenerate** (multiple codons per amino acid) and **unambiguous**; wobble pairing at the third codon position.
- Ribosomes: prokaryotes 70S (30S + 50S); eukaryotes 80S (40S + 60S). Sites: A (aminoacyl), P (peptidyl), E (exit).
- Aminoacyl-tRNA synthetases charge tRNAs (uses ATP). Peptidyl transferase activity is in the large subunit rRNA (ribozyme).
- Stages: initiation, elongation, termination (release factors). Post-translational modifications: phosphorylation, glycosylation, cleavage, signal sequence removal.

Codon table (mRNA, 5'→3')

First base	Second: U	Second: C	Second: A	Second: G
U	UUU, UUC: Phe UUA, UUG: Leu	UCU, UCC, UCA, UCG: Ser	UAU, UAC: Tyr UAA, UAG: Stop	UGU, UGC: Cys UGA: Stop UGG: Trp
C	CUU, CUC, CUA, CUG: Leu	CCU, CCC, CCA, CCG: Pro	CAU, CAC: His CAA, CAG: Gln	CGU, CGC, CGA, CGG: Arg
A	AUU, AUC, AUA: Ile AUG: Met (start)	ACU, ACC, ACA, ACG: Thr	AAU, AAC: Asn AAA, AAG: Lys	AGU, AGC: Ser AGA, AGG: Arg
G	GUU, GUC, GUA, GUG: Val	GCU, GCC, GCA, GCG: Ala	GAU, GAC: Asp GAA, GAG: Glu	GGU, GGC, GGA, GGG: Gly

The exam does not supply a codon table unless a passage includes one. Memorize AUG and the three stops; recognize the rest. Only Met (AUG) and Trp (UGG) have a single codon; Leu, Ser, and Arg have six each. Because the third base usually doesn't matter, many third-position point mutations are silent.

MNEMONIC

Stop codons: U Are Away, U Are Gone, U Go Away (UAA, UAG, UGA).

Mutations

Type	Effect
Silent	Codon change, same amino acid
Missense	Different amino acid (e.g., sickle cell Glu → Val)
Nonsense	Premature stop codon
Frameshift	Insertion/deletion not a multiple of 3; alters all downstream codons
Chromosomal	Deletion, duplication, inversion, translocation

- **Mutagens vs carcinogens:** mutagens (UV light, ionizing radiation, many chemicals) damage DNA; most carcinogens act as mutagens, which is why the Ames test screens chemicals for mutagenicity.
- **Inborn errors of metabolism:** inherited enzyme defects that block a pathway. Example: phenylketonuria (phenylalanine hydroxylase deficiency), managed with a low-phenylalanine diet.
- **Advantageous vs deleterious** depends on environment: sickle-cell heterozygotes are protected against malaria, which keeps the allele common where malaria is endemic.

Gene Regulation

- **lac operon (inducible):** repressor binds operator unless lactose (allolactose) is present; high glucose lowers cAMP, so CAP can't activate transcription. Transcribed when lactose is present AND glucose is low (Jacob-Monod model).
- **trp operon (repressible):** tryptophan acts as corepressor, turning the operon off when tryptophan is abundant.
- **Eukaryotic regulation:** transcription factors (DNA-binding and activation domains), enhancers/silencers, histone acetylation (opens chromatin, ↑ transcription), DNA methylation (silences, often at CpG islands), microRNAs/siRNAs and other noncoding RNAs.
- **Gene duplication and amplification:** extra copies can evolve new functions (gene families) or drive cancer when an oncogene is amplified (HER2 in some breast cancers).

- **Cancer** is a failure of normal cellular controls: oncogenes (gain-of-function, e.g., RAS) vs tumor suppressors (loss-of-function, e.g., p53, RB).

Biotechnology Techniques

Technique	Purpose / principle
PCR	Amplifies DNA: denature (~95 °C), anneal primers (~55 °C), extend with heat-stable Taq polymerase (~72 °C); exponential copies
qPCR / RT-PCR	Quantifies DNA in real time / converts RNA to cDNA first to measure expression
Gel electrophoresis	Separates DNA by size (DNA is negative, migrates toward the + anode; small fragments travel farther)
SDS-PAGE	SDS denatures and coats proteins with negative charge → separation by mass only
Native PAGE	Separates folded proteins by size and charge
Isoelectric focusing	pH gradient; proteins stop at their pI
Southern / Northern / Western blot	Detects DNA / RNA / protein (antibodies for Westerns)
ELISA	Antibody-based detection and quantification of antigen or antibody
Restriction enzymes	Cut at palindromic sequences; sticky or blunt ends
Cloning with plasmids	Insert gene + antibiotic-resistance marker into vector; transform bacteria; select; express the cloned gene
DNA libraries	Genomic libraries hold all DNA fragments; cDNA libraries are reverse-transcribed mRNA, lack introns, and can be expressed in bacteria
CRISPR-Cas9	Guide RNA directs Cas9 to cut specific DNA; enables knockouts and edits
DNA sequencing (Sanger)	Dideoxynucleotides (no 3' -OH) terminate chains
Knockout / transgenic animals	Remove or add genes to study function
Microarrays / RNA-seq	Measure expression of many genes simultaneously
Stem cells	Embryonic (pluripotent) and induced pluripotent stem cells for research and regenerative therapy

Applications and ethics: DNA technology is used in medicine (diagnostics, gene therapy, recombinant drugs such as insulin), forensics, agriculture (GMOs), and environmental cleanup. Ethical and safety questions include privacy of genetic information, germline editing, unintended ecological effects, and informed consent.

MNEMONIC

SNOW DROP: Southern-DNA, Northern-RNA, O-O, Western-Protein.

SECTION 7

Cell Biology, Genetics, and Evolution

Cell Theory and Cell Types

- **Cell theory:** all living things are made of cells; the cell is the basic unit of life; cells arise from pre-existing cells; cells carry DNA as genetic material.
- **Prokaryotes** (bacteria, archaea): no nucleus or membrane-bound organelles; circular chromosome in a nucleoid; 70S ribosomes; plasmids.
- **Eukaryotes:** nucleus, membrane-bound organelles, linear chromosomes, 80S cytoplasmic ribosomes, mitotic division.

Organelle	Function
Nucleus / nucleolus	Houses DNA behind a double-membrane envelope with nuclear pores; transcription / rRNA synthesis and ribosome assembly
Rough ER	Ribosome-studded; synthesizes secreted, membrane, and lysosomal proteins
Smooth ER	Lipid and membrane synthesis, detoxification (liver), Ca^{2+} storage (sarcoplasmic reticulum in muscle)
Golgi apparatus	Modifies, sorts, and packages proteins (glycosylation); cis receives, trans ships
Mitochondria	ATP production; inner membrane folds (cristae) hold the ETC; own circular DNA (maternally inherited) and self-replicate; apoptosis (cytochrome c release)
Lysosomes	Acidic hydrolases; digest macromolecules and organelles (autophagy)
Peroxisomes	Break down very-long-chain fatty acids and H_2O_2 ; synthesize plasmalogens
Cytoskeleton	Microfilaments (actin: muscle, cleavage furrow), microtubules (tubulin: spindle, cilia/flagella 9+2), intermediate filaments (keratin, desmin; structural)
Centrosome / centrioles	Microtubule organizing center (9 triplets)

MNEMONIC

Mitochondria and chloroplasts support endosymbiotic theory: double membranes, own circular DNA, 70S-like ribosomes, and binary-fission-like division.

Tissues: Epithelial and Connective

Epithelial tissue covers surfaces and lines cavities. It is polarized (apical vs basal side), sits on a basement membrane, has no blood vessels, and is joined by tight junctions. Epithelia are named by layers (simple, stratified, pseudostratified) and cell shape (squamous, cuboidal, columnar).

Type	Location	Function
Simple squamous	Alveoli, capillary endothelium	Diffusion and filtration
Simple cuboidal	Kidney tubules, gland ducts	Secretion and absorption
Simple columnar	Stomach and intestine lining	Absorption (microvilli), secretion

Type	Location	Function
Pseudostratified ciliated columnar	Trachea, bronchi	Mucociliary escalator
Stratified squamous	Skin epidermis, esophagus, mouth	Protection from abrasion
Transitional	Bladder, ureters	Stretching

Connective tissue has cells scattered in an extracellular matrix of fibers and ground substance, mostly made by fibroblasts. Collagen gives tensile strength; elastin gives stretch. Types: loose connective tissue, dense connective tissue (tendons, ligaments), cartilage, bone, adipose tissue, and blood. In organs, epithelial cells usually form the functional parenchyma and connective tissue forms the supporting stroma. Muscle and nervous tissue are covered in Section 8.

Membranes and Transport

- **Fluid mosaic model:** phospholipid bilayer with embedded proteins, cholesterol, and glycolipids. Cholesterol buffers fluidity (reduces it at high temperature, raises it at low).
- **Cell junctions:** tight junctions (seal, prevent paracellular flow), desmosomes (anchor via intermediate filaments), gap junctions (connexons; direct cytoplasmic communication).
- **Tonicity:** hypotonic solution → cell swells; hypertonic → cell shrinks (crenation); isotonic → no net change.
- **Membrane receptors** relay outside signals inward (see Biosignaling, Section 8); the membrane potential comes from ion gradients maintained by pumps and leak channels.

Transport	Energy	Examples
Simple diffusion	Passive, down gradient	O ₂ , CO ₂ , small nonpolar molecules, steroids
Osmosis	Passive	Water (often via aquaporins)
Facilitated diffusion	Passive, via channels/carriers; saturable	GLUT transporters, ion channels
Primary active transport	Direct ATP hydrolysis	Na ⁺ /K ⁺ -ATPase: 3 Na ⁺ out, 2 K ⁺ in
Secondary active transport	Uses an existing gradient	Symport (SGLT: Na ⁺ /glucose) and antiport (Na ⁺ /Ca ²⁺ exchanger)
Endocytosis / exocytosis	ATP	Phagocytosis, pinocytosis, receptor-mediated (clathrin); vesicle secretion

Cell Cycle and Division

- **Interphase:** G1 (growth; restriction point), S (DNA replication), G2 (prep for mitosis). G0: non-dividing, growth-arrested (neurons, most muscle).
- **Checkpoints:** G1/S (p53 checks DNA damage), G2/M, and spindle (metaphase) checkpoint. Cyclins activate cyclin-dependent kinases (CDKs). Cancer cells lose these controls.
- **Mitosis (PMAT):** **Prophase** (condense, spindle forms from centrioles and asters, nuclear envelope breaks down), **Metaphase** (chromosomes align; kinetochores attach), **Anaphase** (sister chromatids separate), **Telophase** (nuclear envelopes reform), then cytokinesis.

	Mitosis	Meiosis
Purpose	Growth, repair, asexual reproduction	Gamete formation
Divisions	One	Two (meiosis I is reductional, II is equational)

	Mitosis	Meiosis
Daughter cells	2 diploid (2n), identical	4 haploid (n), genetically distinct
Homologous pairing	No	Synapsis via the synaptonemal complex and crossing over in prophase I (tetrads/bivalents)
Separation	Sister chromatids	Homologs in anaphase I; sister chromatids in anaphase II

Nondisjunction (failure to separate) causes aneuploidy (e.g., trisomy 21). Apoptosis is programmed cell death via caspases; necrosis is uncontrolled, inflammatory death.

Evidence That DNA Is the Genetic Material

Experiment	Setup	Conclusion
Griffith (1928)	Heat-killed virulent (S) pneumococcus mixed with a live harmless (R) strain killed mice	A "transforming principle" passes between bacteria
Avery, MacLeod, and McCarty (1944)	Destroyed each molecule class in S-strain extract	Only DNase blocked transformation: DNA is the transforming principle
Hershey and Chase (1952)	Labeled phage protein with ^{35}S and DNA with ^{32}P	Only ^{32}P entered bacteria: DNA is the phage genetic material
Meselson and Stahl (1958)	Grew bacteria in ^{15}N , then ^{14}N , and separated DNA by density	Hybrid-density DNA after one round: replication is semiconservative

Mendelian and Non-Mendelian Genetics

Term	Definition
Gene / allele / locus	Unit of heredity / variant form / chromosomal location
Genotype / phenotype	Allele combination / observable trait
Wild-type	The most common allele or phenotype in a natural population
Law of segregation	Allele pairs separate during gamete formation (anaphase I)
Law of independent assortment	Genes on different chromosomes assort independently (violated by linkage)
Complete dominance	Heterozygote shows dominant phenotype
Incomplete dominance	Heterozygote is intermediate (red $\times$ white $\rightarrow$ pink)
Codominance	Both alleles expressed (AB blood type)
Penetrance	% of individuals with a genotype who show the phenotype
Expressivity	Degree of phenotypic variation among those who show it
Leakage	Gene flow from one species into another through fertile hybrids
Epistasis	One gene masks another gene's expression
Pleiotropy	One gene affects multiple traits
Test cross	Unknown $\times$ homozygous recessive reveals unknown genotype
Gene pool	All alleles present in a population

- Monohybrid $Aa \times Aa$: 3:1 phenotype, 1:2:1 genotype. Dihybrid $AaBb \times AaBb$: 9:3:3:1. $P \rightarrow F_1 \rightarrow F_2$ generations.

- Recombination frequency $\propto$ distance between linked genes; 1% recombination = 1 centimorgan (map unit). Max 50%. Double crossovers between distant genes can restore the parental arrangement, so far-apart genes are underestimated.
- **Sex determination:** XX female, XY male; the Y chromosome carries very few genes (including SRY). X-linked recessive traits (hemophilia, color blindness): mostly males affected; no father-to-son transmission; carrier mothers pass to 50% of sons.
- **Cytoplasmic (extranuclear) inheritance:** mitochondrial genes come only from the mother.
- Pedigree clues: skips generations $\rightarrow$ recessive; every generation $\rightarrow$ dominant; only mothers pass it to all children $\rightarrow$ mitochondrial.

Population Genetics and Evolution

Concept	Details
Hardy-Weinberg equations	$p + q = 1$; $p^2 + 2pq + q^2 = 1$ ($p^2 = AA$, $2pq = Aa$, $q^2 = aa$)
H-W assumptions	Large population, random mating, no mutation, no migration (gene flow), no natural selection
Natural selection	Differential reproductive success; fitness = reproductive success, not strength. Evolutionary success is an allele's rising share of the next generation's gene pool
Stabilizing / directional / disruptive	Favors average / one extreme / both extremes (can drive speciation)
Genetic drift	Random allele frequency changes, strongest in small populations; includes bottleneck and founder effects
Inbreeding / outbreeding	Mating with relatives raises homozygosity (and recessive disease); outbreeding increases variation
Polymorphism	Two or more distinct forms of a trait coexisting in a population
Speciation	Allopatric (geographic separation), sympatric (same area); maintained by reproductive isolation; adaptation and specialization follow
Prezygotic barriers	Temporal, habitat, behavioral, mechanical, gametic isolation
Postzygotic barriers	Hybrid inviability, hybrid sterility, hybrid breakdown
Evolution patterns	Divergent, convergent (analogous structures), parallel; homologous structures share ancestry
Inclusive fitness and group selection	Inclusive fitness counts relatives' reproductive success (kin selection, altruism); group selection proposes traits that benefit the group
Molecular clock	Mutations accumulate at a roughly steady rate, so sequence differences estimate time since divergence

HIGH-YIELD TIP

On H-W problems, start from the homozygous recessive frequency: $q = \sqrt{\text{frequency of recessive phenotype}}$. If 1 in 10,000 have a recessive disorder, $q = 0.01$, $p \approx 0.99$, and carriers ($2pq$) $\approx 2\%$.

Microbiology

Feature	Gram-positive	Gram-negative
Cell wall	Thick peptidoglycan; teichoic acids	Thin peptidoglycan between two membranes
Outer membrane	No	Yes, with lipopolysaccharide (endotoxin)
Gram stain	Purple	Pink/red

- **Archaea vs bacteria:** archaea lack peptidoglycan, use ether-linked membrane lipids, and have histone-like proteins; many live in extreme environments.
- **Shapes:** cocci (spherical), bacilli (rod), spirilli (spiral). **Oxygen use:** obligate aerobes, obligate anaerobes, facultative anaerobes, aerotolerant anaerobes.
- **Motility:** bacterial flagella are rotary motors powered by the proton gradient; chemotaxis steers bacteria toward attractants and away from repellents.
- **Lifestyles:** bacteria can be free-living, symbiotic (gut flora), or parasitic (pathogens).
- **Reproduction:** binary fission. **Genetic exchange:** transformation (take up free DNA), transduction (virus carries DNA), conjugation (sex pilus; F plasmid). Transposons move within genomes. Plasmids spread antibiotic resistance quickly.
- **Growth curve phases:** lag, exponential (log), stationary, death.
- **Viruses:** genetic material (DNA or RNA) in a capsid, sometimes an envelope; no organelles; much smaller than bacteria; obligate intracellular parasites. Bacteriophages have a head, tail, and tail fibers and inject only their genome. Lytic cycle (virulent, lyses host) vs lysogenic (provirus/prophage integrates).
- **Retroviruses** (e.g., HIV): ss(+)RNA → DNA via reverse transcriptase, integrates into host genome. (+) sense RNA acts directly as mRNA; (–) sense needs RNA replicase carried in the virion.
- **Prions:** infectious misfolded proteins. **Viroids:** small circular RNAs that infect plants.
- **Fungi:** eukaryotic, chitin cell walls, can reproduce sexually or asexually (budding).

SECTION 8

Organ Systems

Nervous System

Structure	Function
Dendrites	Receive signals
Soma (cell body)	Contains nucleus; integrates signals
Axon hillock	Summation site; action potential initiated if threshold reached
Axon / myelin	Conducts impulse; myelin (oligodendrocytes in CNS, Schwann cells in PNS) enables saltatory conduction at nodes of Ranvier
Axon terminal	Releases neurotransmitter into synapse
Glia	Astrocytes (blood-brain barrier, nutrients), microglia (immune), ependymal cells (CSF), oligodendrocytes, Schwann cells

Resting and Action Potentials

- Resting potential ≈ -70 mV, maintained by K^+ leak channels and Na^+/K^+ -ATPase. Na^+ is high outside; K^+ is high inside.
- Nernst equation (37 °C): $E = (61.5 \text{ mV}/z) \log([ion]_{out}/[ion]_{in})$. Goldman equation weights ions by permeability.
- **Sequence:** depolarization to threshold (≈ -55 mV) $\rightarrow$ voltage-gated Na^+ channels open (rise to $\approx +35$ mV) $\rightarrow$ Na^+ channels inactivate, voltage-gated K^+ channels open (repolarization) $\rightarrow$ hyperpolarization (undershoot) $\rightarrow$ return to rest.
- **Absolute refractory period:** no new AP possible (Na^+ channels inactivated). **Relative refractory period:** stronger stimulus needed.
- **All-or-none:** stimulus intensity is encoded by frequency, not amplitude. Conduction speed $\uparrow$ with myelination and axon diameter. Excitatory and inhibitory inputs sum (temporal and spatial summation).
- **Synapse:** AP $\rightarrow$ voltage-gated Ca^{2+} influx $\rightarrow$ vesicle exocytosis $\rightarrow$ neurotransmitter binds receptors $\rightarrow$ termination by reuptake, enzymatic breakdown (acetylcholinesterase), or diffusion.

Organization

Division	Features
Central nervous system	Brain and spinal cord
Somatic nervous system	Voluntary skeletal muscle; ACh at neuromuscular junction
Sympathetic (fight or flight)	Thoracolumbar origin; $\uparrow$ HR, bronchodilation, pupil dilation, $\downarrow$ digestion, glycogenolysis; ACh preganglionic, NE postganglionic (adrenal medulla releases epinephrine)
Parasympathetic (rest and digest)	Craniosacral origin (vagus nerve); $\downarrow$ HR, $\uparrow$ digestion, pupil constriction; ACh pre- and postganglionic
Enteric nervous system	The gut's own neuron network; controls peristalsis and secretion, modulated by autonomic input
Reflex arcs	Monosynaptic (knee jerk: sensory $\rightarrow$ motor) or polysynaptic (withdrawal, with interneurons); handled by the spinal cord with supraspinal modulation

Brain Regions

Region	Function
Frontal lobe	Executive function, planning, personality (prefrontal cortex); primary motor cortex; Broca's area (speech production, usually left)
Parietal lobe	Somatosensory cortex; spatial processing
Temporal lobe	Auditory cortex; Wernicke's area (language comprehension); memory
Occipital lobe	Visual cortex
Thalamus	Relay station for sensory info (except smell)
Hypothalamus	Homeostasis: hunger (lateral: hunger; ventromedial: satiety), thirst, temperature, circadian rhythm (SCN), endocrine control
Hippocampus	Forming new explicit long-term memories
Amygdala	Fear, aggression, emotional memory
Basal ganglia	Smooth movement initiation (Parkinson's: substantia nigra dopamine loss)
Cerebellum	Coordination, balance, motor learning
Brainstem	Medulla (breathing, heart rate, BP), pons (relay, sleep), midbrain (superior and inferior colliculi: reflexes to sight and sound)
Corpus callosum	Connects hemispheres

Forebrain: cortex, thalamus, hypothalamus, limbic system, basal ganglia. **Midbrain:** colliculi. **Hindbrain:** pons, medulla, cerebellum.

Neurotransmitters

Neurotransmitter	Key roles / disorders
Acetylcholine	Muscle contraction, parasympathetic, memory (↓ in Alzheimer's)
Dopamine	Reward, movement (↓ Parkinson's; ↑ activity linked to schizophrenia positive symptoms)
Serotonin	Mood, sleep, appetite (↓ in depression)
Norepinephrine / epinephrine	Alertness, fight-or-flight (↓ NE in depression, ↑ in mania)
GABA / glycine	Main inhibitory (brain / spinal cord); GABA targeted by benzodiazepines, alcohol
Glutamate	Main excitatory; learning (NMDA receptors, LTP)
Endorphins	Natural opioids; pain relief

Biosignaling: Receptor Types

Where the receptor sits decides how fast the response is: membrane channels act in milliseconds, nuclear receptors in hours.

Receptor	Mechanism	Speed	Examples
Ligand-gated ion channel	Ligand binding opens a pore	Millisecond s	Nicotinic ACh receptor, GABA-A

Receptor	Mechanism	Speed	Examples
Voltage-gated ion channel	Membrane depolarization opens a pore	Milliseconds	Na ⁺ and K ⁺ channels in the action potential; Ca ²⁺ at the axon terminal
G protein-coupled receptor (7 transmembrane passes)	Ligand makes Gα swap GDP for GTP; Gα acts on an effector	Seconds	Gs: ↑ adenylyl cyclase → cAMP → PKA (glucagon; epinephrine at β receptors). Gi: ↓ cAMP. Gq: phospholipase C → IP ₃ (Ca ²⁺ release from ER) + DAG (activates PKC)
Receptor tyrosine kinase (receptor enzyme)	Ligand causes dimerization and autophosphorylation, starting cascades such as Ras → MAPK	Minutes	Insulin, growth factors (EGF)
Intracellular (nuclear) receptor	Hormone-receptor complex binds DNA response elements and changes transcription	Hours	Steroid hormones, thyroid hormone

- Second messengers amplify signals: one hormone molecule can trigger thousands of cAMP molecules.
- Signals end when Gα hydrolyzes its GTP and phosphodiesterase breaks down cAMP (caffeine inhibits phosphodiesterase).
- Many oncogenes are receptors or signaling proteins stuck in the "on" state (RAS).

Sensory Systems

- **Eye pathway:** cornea → aqueous humor → pupil (iris) → lens (accommodation via ciliary muscles) → vitreous humor → retina. **Rods:** low light, black/white, peripheral. **Cones:** color, detail, concentrated in the fovea. Blind spot: optic disc.
- **Retina signal path:** photoreceptors → bipolar cells → ganglion cells → optic nerve → optic chiasm (nasal fibers cross) → lateral geniculate nucleus (thalamus) → visual cortex.
- **Ear pathway:** pinna → auditory canal → tympanic membrane → ossicles (malleus, incus, stapes) → oval window → cochlea (hair cells on basilar membrane; base = high pitch, apex = low) → auditory nerve → medial geniculate nucleus → auditory cortex. Vestibule and semicircular canals: balance and rotation.
- **Receptor types:** mechanoreceptors, chemoreceptors, nociceptors (pain), thermoreceptors, osmoreceptors, photoreceptors. Olfaction bypasses the thalamus.

Endocrine System

Peptide hormones (hydrophilic) bind surface receptors and use second messengers (cAMP, IP₃/Ca²⁺); fast, short-lived. **Steroid hormones** (lipophilic, from cholesterol) cross membranes and bind intracellular receptors to alter transcription; slow, long-lasting, carried in blood by proteins. **Amino-acid-derived hormones** vary: catecholamines act like peptides; thyroid hormones act like steroids. Hormones reach target tissues through the blood and act only where matching receptors exist.

Gland	Hormone	Main action
Hypothalamus	GnRH, TRH, CRH, GHRH, dopamine (PIF), somatostatin	Control anterior pituitary via hypophyseal portal system
Anterior pituitary	FSH, LH	Gametogenesis; ovulation and sex steroid production
	ACTH	Adrenal cortex → cortisol
	TSH	Thyroid → T ₃ /T ₄
	Prolactin	Milk production

Gland	Hormone	Main action
	Endorphins	Pain inhibition
	Growth hormone	Growth of bone and muscle; ↑ blood glucose
Posterior pituitary (stores hypothalamic hormones)	ADH (vasopressin)	↑ water reabsorption in collecting duct (aquaporins)
	Oxytocin	Uterine contraction, milk ejection, bonding (positive feedback)
Thyroid	T ₃ /T ₄ ; calcitonin	↑ metabolic rate; ↓ blood Ca ²⁺
Parathyroid	PTH	↑ blood Ca ²⁺ (bone resorption, kidney reabsorption, activates vitamin D)
Adrenal cortex	Cortisol, aldosterone, androgens	Stress/glucose; Na ⁺ reabsorption and K ⁺ secretion; sex hormones
Adrenal medulla	Epinephrine, norepinephrine	Sympathetic response
Pancreas (islets)	Insulin (β), glucagon (α), somatostatin (δ)	↓ glucose; ↑ glucose; inhibits both
Gonads	Testosterone; estrogen, progesterone	Male traits; female traits, endometrial growth and maintenance
Pineal	Melatonin	Circadian rhythm
Kidney / heart	Erythropoietin, renin / ANP	↑ RBC production, RAAS / ↓ blood volume (natriuresis)

MNEMONIC

FLAT PEG: anterior pituitary hormones are FSH, LH, ACTH, TSH, Prolactin, Endorphins, Growth hormone. FLAT hormones are tropic (act on other glands).

Cardiovascular System

- **Blood flow:** right atrium → tricuspid → right ventricle → pulmonary valve → pulmonary artery → lungs → pulmonary veins → left atrium → mitral (bicuspid) → left ventricle → aortic valve → aorta → body → venae cavae.
- Arteries carry blood away from the heart (usually oxygenated, except pulmonary arteries); veins carry blood toward it (valves prevent backflow). Arterioles are the main source of peripheral resistance; capillaries are lined by a single layer of endothelial cells.
- **Conduction:** SA node (pacemaker) → AV node (delay lets ventricles fill) → bundle of His → bundle branches → Purkinje fibers. Intercalated discs with gap junctions allow syncytial contraction.
- **Systole:** ventricles contract (AV valves close → "lub"). **Diastole:** ventricles relax (semilunar valves close → "dub").
- **Cardiac output:** $CO = HR \times SV$. Mean arterial pressure $\approx CO \times \text{total peripheral resistance}$.
- **Blood:** plasma (≈55%), erythrocytes (no nucleus or mitochondria; hemoglobin carries O₂; made in bone marrow, destroyed in the spleen), leukocytes (immune), platelets (clotting; fibrinogen → fibrin via thrombin).
- CO₂ travels mainly as bicarbonate: $CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$ (carbonic anhydrase in RBCs).
- **Capillary exchange (Starling forces):** hydrostatic pressure pushes fluid out at the arterial end; oncotic pressure pulls it back at the venous end; excess returns via lymph. Skin capillaries also exchange heat (vasodilation and vasoconstriction).

Hemoglobin O ₂ curve shift	Causes	Meaning
Right shift (↓ affinity)	↑ CO ₂ , ↑ H ⁺ (↓ pH, Bohr effect), ↑ temperature, ↑ 2,3-BPG, exercise	More O ₂ unloaded to tissues
Left shift (↑ affinity)	Opposite conditions, fetal hemoglobin, carbon monoxide	O ₂ held more tightly

Blood type	Antigens on RBC	Antibodies in plasma	Can receive from
A	A	Anti-B	A, O
B	B	Anti-A	B, O
AB (universal recipient)	A and B	None	All
O (universal donor)	None	Anti-A and anti-B	O

Rh factor: Rh⁻ mothers can make anti-Rh antibodies after exposure to an Rh⁺ fetus, threatening later Rh⁺ pregnancies (erythroblastosis fetalis).

Lymphatic System

Lymphatics return the fluid that capillaries leak, so blood volume and tissue fluid stay balanced.

- **Structure:** blind-ended lymphatic capillaries collect interstitial fluid; one-way vessels with valves carry it through lymph nodes and empty into the venous system via the thoracic duct (into the left subclavian vein) and the right lymphatic duct.
- **No pump:** lymph moves by skeletal muscle contraction, breathing pressure changes, and valves, just like veins.
- **Functions:** equalizing fluid distribution; transporting proteins and large glycerides (chylomicrons enter lacteals in the intestinal villi); producing and housing lymphocytes; returning materials to the blood.
- **Lymph nodes** filter lymph past B and T cells; swollen nodes signal immune activation. Blocked lymph drainage causes edema.

Respiratory System

- **Path:** nares → pharynx → larynx → trachea → bronchi → bronchioles → alveoli (gas exchange by simple diffusion down partial pressure gradients). Surfactant lowers surface tension and prevents alveolar collapse.
- **Inhalation is active:** diaphragm contracts (flattens) and external intercostals lift ribs → thoracic volume ↑ → intrapleural pressure ↓ → air flows in (negative-pressure breathing). Quiet exhalation is passive.
- **Volumes:** tidal volume, IRV, ERV, residual volume (never exhaled); vital capacity = TV + IRV + ERV; total lung capacity = VC + RV.
- Breathing is driven mostly by CO₂/pH (central chemoreceptors in the medulla); severe hypoxemia also stimulates peripheral chemoreceptors.
- **pH regulation:** hyperventilation blows off CO₂ → raises pH (respiratory alkalosis); hypoventilation → respiratory acidosis. The lungs compensate within minutes; the kidneys within days.
- **Thermoregulation:** nasal and tracheal capillary beds warm incoming air; evaporation from airways (panting in animals) sheds heat.
- **Defense:** mucociliary escalator, nasal hairs, alveolar macrophages, lysozyme.

Renal System

Nephron segment	Function
Glomerulus / Bowman's capsule	Filtration by pressure; blocks cells and large proteins
Proximal convoluted tubule	Reabsorbs most Na ⁺ , water, glucose, amino acids, bicarbonate; secretes H ⁺ , K ⁺ , drugs, urea
Descending loop of Henle	Permeable to water, not salt; water leaves into hypertonic medulla
Ascending loop of Henle	Impermeable to water; actively pumps out Na ⁺ /Cl ⁻ (thick segment); creates medullary gradient (countercurrent multiplier)
Distal convoluted tubule	Aldosterone-responsive Na ⁺ reabsorption; K ⁺ and H ⁺ secretion
Collecting duct	ADH inserts aquaporins → concentrated urine; final water balance

- **RAAS:** ↓ BP → juxtaglomerular cells release renin → angiotensinogen → angiotensin I → (ACE, lungs) angiotensin II → vasoconstriction + aldosterone release → ↑ Na⁺ and water reabsorption → ↑ BP.
- ADH ↑ water reabsorption only (lowers plasma osmolarity). Aldosterone ↑ Na⁺ and water together (raises volume, not osmolarity). ANP promotes Na⁺ excretion.
- Kidney regions: cortex (glomeruli, convoluted tubules) and medulla (loops, collecting ducts). **Urine path:** kidney → ureter → bladder → urethra, with sphincter muscles controlling release. Kidneys also secrete EPO and activate vitamin D.

Digestive System

Location	Enzyme / secretion	Action
Mouth	Salivary amylase, lingual lipase	Starch digestion begins; mechanical chewing; saliva lubricates
Stomach	Pepsin (from pepsinogen, chief cells); HCl and intrinsic factor (parietal cells); mucus	Protein digestion; kills pathogens; B12 absorption; mucus protects the lining
Pancreas (acinar cells → duodenum)	Trypsin, chymotrypsin, carboxypeptidase, pancreatic amylase, lipase, bicarbonate	Main digestion of all macronutrients; neutralizes acid
Small intestine brush border	Disaccharidases (lactase, sucrase, maltase), aminopeptidase, dipeptidase, enteropeptidase	Final digestion; enteropeptidase activates trypsinogen
Liver / gallbladder	Bile (bile salts)	Emulsifies fats (not an enzyme); stored in gallbladder

GI hormone	Source	Action
Gastrin	Stomach (G cells)	↑ HCl secretion and gastric motility
Secretin	Duodenum (S cells)	↑ pancreatic bicarbonate; ↓ gastric acid
Cholecystokinin (CCK)	Duodenum	↑ bile release and pancreatic enzymes; promotes satiety
Ghrelin / leptin	Stomach / adipose	Stimulates hunger / suppresses hunger

- **Absorption:** most occurs in the small intestine (duodenum → jejunum → ileum), aided by villi and microvilli. Simple sugars and amino acids enter capillaries (→ hepatic portal vein); fats enter lacteals as chylomicrons (→ lymph). Peristalsis moves food along.
- Large intestine absorbs water and electrolytes; gut bacteria produce vitamin K and biotin. Rectum stores feces until elimination.

- **Liver functions:** glycogen storage, gluconeogenesis, detoxification, bile production, plasma protein synthesis (albumin, clotting factors), urea synthesis, bilirubin conjugation.

Immune System

Branch	Components	Features
Innate (nonspecific)	Skin, mucus, lysozyme, complement, macrophages, neutrophils, dendritic cells, NK cells, mast cells, eosinophils, fever, inflammation	Fast, no memory; recognizes common patterns (toll-like receptors)
Humoral adaptive	B cells → plasma cells (antibodies) and memory B cells	Targets extracellular pathogens; matures in bone marrow
Cell-mediated adaptive	Helper T (CD4 ⁺ , recognize MHC II), cytotoxic T (CD8 ⁺ , recognize MHC I), regulatory T	Targets infected and cancerous cells; matures in thymus

- **MHC I:** on all nucleated cells, presents endogenous (internal) antigens. **MHC II:** on antigen-presenting cells (macrophages, dendritic cells, B cells), presents exogenous antigens.
- **Clonal selection:** an antigen activates only the lymphocytes whose receptors match it, which then multiply. Self-reactive cells are normally eliminated; failure causes autoimmunity.
- **Antibodies:** two heavy + two light chains; variable region binds antigen. Isotypes: IgM (first response, pentamer), IgG (most abundant, crosses placenta), IgA (secretions, breast milk), IgE (allergy, parasites), IgD (B-cell receptor).
- Active immunity (infection or vaccine; produces memory) vs passive immunity (transferred antibodies, e.g., maternal IgG; temporary).
- Allergy: IgE-mediated mast cell histamine release. Lymph nodes filter lymph; spleen filters blood; bone marrow and thymus produce and mature lymphocytes.

MNEMONIC

Rule of 8: CD4 × MHC II = 8; CD8 × MHC I = 8.

Musculoskeletal System

Feature	Skeletal	Cardiac	Smooth
Striated?	Yes	Yes	No
Control	Voluntary (somatic)	Involuntary (autonomic)	Involuntary (autonomic)
Nuclei	Multinucleated	1-2 per cell	1 per cell
Special features	Neuromuscular junction	Intercalated discs; automaticity	Myogenic activity; calmodulin regulation

- **Sarcomere:** Z-lines bound it; thin filaments (actin) and thick (myosin). During contraction the H-zone and I-band shorten; the A-band stays constant.
- **Contraction:** ACh → end-plate depolarization → AP spreads down T-tubules → sarcoplasmic reticulum releases Ca²⁺ → Ca²⁺ binds troponin → tropomyosin shifts, exposing myosin-binding sites → cross-bridge cycling → Ca²⁺ pumped back.
- **Cross-bridge cycle:** release of P_i triggers the power stroke; ADP is released at its end; ATP binding detaches myosin; ATP hydrolysis re-cocks the head.
- **Fiber types:** slow-twitch (red, oxidative, myoglobin- and mitochondria-rich) vs fast-twitch (white, glycolytic). Summation and tetanus result from high stimulation frequency. **Oxygen debt:** after intense exercise, extra O₂ is needed to clear lactate and restore creatine phosphate; fatigue sets in as ATP runs short.

- Muscles also support venous return (skeletal muscle pump) and generate heat (shivering).
- **Bone:** osteoblasts build, osteoclasts break down, osteocytes maintain. Bone is a calcium-phosphate (hydroxyapatite) matrix on collagen; it stores calcium. Compact bone uses osteons (Haversian systems). Red marrow: hematopoiesis; yellow marrow: fat.
- **Joints:** fibrous (immovable), cartilaginous (slightly movable), synovial (freely movable). Vertebrates have endoskeletons; arthropods have exoskeletons.
- Cartilage (chondrocytes; avascular), ligaments (bone to bone), tendons (muscle to bone).

MNEMONIC

Osteoblasts build, osteoclasts chew. PTH raises blood Ca^{2+} ("PTH pulls Ca from bone"); calcitonin "tones down" blood Ca^{2+} .

Reproduction and Development

- **Male pathway (SEVEN UP):** Seminiferous tubules → Epididymis → Vas deferens → Ejaculatory duct → (Nothing) → Urethra → Penis. Sertoli cells nourish sperm (stimulated by FSH); Leydig cells make testosterone (stimulated by LH).
- **Spermatogenesis:** produces 4 functional sperm per primary spermatocyte, continuously from puberty.
- **Oogenesis:** primary oocytes arrest in prophase I from before birth until puberty; secondary oocytes arrest in metaphase II until fertilization. Produces 1 ovum + polar bodies. The ovum supplies nearly all cytoplasm and mitochondria; the sperm contributes mostly its nucleus.
- **Menstrual cycle:** follicular phase (FSH → follicle growth, rising estrogen) → LH surge triggers ovulation (~day 14; estrogen shows positive feedback here) → luteal phase (corpus luteum secretes progesterone and estrogen) → menses if no pregnancy. hCG from the embryo maintains the corpus luteum in pregnancy. Oxytocin drives parturition; prolactin and oxytocin drive lactation.
- Fertilization typically occurs in the ampulla of the fallopian tube. Acrosome reaction lets sperm penetrate the corona radiata and zona pellucida; cortical reaction blocks polyspermy.

Embryology

- Zygote → cleavage (more cells, no growth) → morula → blastula/blastocyst (inner cell mass → embryo; trophoblast → placenta/chorion) → implantation → gastrulation → neurulation.
- Gastrulation forms three germ layers. Neurulation: notochord induces ectoderm to form the neural tube (→ CNS); neural crest cells → PNS, melanocytes, adrenal medulla.
- **Cell fate:** determination (commitment) precedes differentiation. Induction: one group of cells influences another. Stem cell potency: totipotent > pluripotent > multipotent. Cells migrate to their final positions guided by chemical signals.
- **Programmed cell death** sculpts structures (separating fingers). **Regenerative capacity** varies widely (salamander limbs vs the human liver). **Senescence** and aging are linked to telomere shortening (the Hayflick limit).
- **Environment-gene interaction:** teratogens (alcohol, some drugs, infections) cause the most harm during the embryonic period when organs form.
- Fetal circulation shunts bypass the lungs and liver: foramen ovale (RA → LA), ductus arteriosus (pulmonary artery → aorta), ductus venosus (bypasses liver).

Germ layer	Gives rise to
Ectoderm ("attracto-derm")	Nervous system, epidermis, hair, nails, lens, inner ear, adrenal medulla
Mesoderm ("means-o-derm")	Muscle, bone, connective tissue, heart and blood vessels, kidneys, gonads, adrenal cortex

Germ layer	Gives rise to
Endoderm ("endernal organs")	Epithelial lining of GI and respiratory tracts, liver, pancreas, thyroid, bladder

Skin and Homeostasis

- **Layers:** epidermis (keratinocytes, melanocytes, Langerhans cells; outer to inner, stratum corneum to basale: "Come, Let's Get Sun Burned"), dermis (sweat glands, hair follicles, receptors), hypodermis (fat for insulation). Skin is nearly waterproof and blocks abrasion and pathogens.
- **Thermoregulation:** heat loss by sweating (evaporation) and vasodilation; heat conservation by vasoconstriction, shivering, piloerection.
- Negative feedback maintains set points (most hormones); positive feedback amplifies (oxytocin in labor, LH surge, clotting cascade).

SECTION 9

Psychology

Sensation and Perception

Term	Definition
Sensation vs perception	Detecting a stimulus (transduction by receptors) vs interpreting it
Absolute threshold	Minimum stimulus intensity detected 50% of the time
Difference threshold (JND)	Smallest detectable change between two stimuli
Weber's law	$\Delta I/I = k$: the JND is a constant proportion of the original stimulus
Signal detection theory	Detection depends on stimulus strength and psychological state; outcomes are hits, misses, false alarms, correct rejections
Sensory adaptation	Decreased response to a constant stimulus
Bottom-up vs top-down processing	Built from raw features vs guided by expectations and experience
Gestalt principles	Proximity, similarity, continuity, closure, figure-ground, prägnanz (simplest interpretation)
Depth cues	Binocular: retinal disparity, convergence. Monocular: relative size, interposition, linear perspective, texture gradient, motion parallax
Feature detectors (Hubel & Wiesel)	Visual cortex neurons respond to lines, edges, motion
Parallel processing	Color, form, motion, and depth analyzed simultaneously ("what" parvocellular vs "where" magnocellular pathways)
Kinesthetic vs vestibular sense	Body position and movement from muscles and joints vs balance and head rotation from the inner ear
Taste and smell	Taste buds (chemoreceptors) detect sweet, salty, sour, bitter, and umami. Olfactory receptors detect airborne chemicals; pheromones signal between members of a species
Pain (gate-control theory)	Spinal cord "gates" can block pain signals; non-painful input like rubbing an injury closes the gate

Attention and Information Processing

- **Selective attention:** focusing on one input while filtering others. Broadbent's early-filter model blocks unattended input; Treisman's attenuation model only weakens it, which explains the cocktail party effect (your name breaks through).
- **Divided attention:** works for automatic, practiced tasks and fails for controlled, novel ones.
- **Inattention blindness** (missing an unexpected object) and **change blindness** (missing changes in a scene) show attention's limits.
- **Information-processing model:** input → encoding → storage → retrieval, following the Atkinson-Shiffrin stages (sensory → short-term → long-term memory). Processing can be serial or parallel.

Consciousness, Sleep, and Drugs

Stage	EEG waves	Features
Awake (alert / relaxed)	Beta / alpha	High frequency, low amplitude
N1	Theta	Light sleep; hypnagogic jerks
N2	Theta with sleep spindles and K-complexes	Most total sleep time
N3 (slow-wave)	Delta	Deep sleep; sleepwalking, night terrors; growth hormone release; declarative memory consolidation
REM	Beta-like ("paradoxical")	Vivid dreaming, muscle atonia, procedural memory consolidation; REM periods lengthen through the night

- Circadian rhythm is set by the suprachiasmatic nucleus; melatonin from the pineal gland rises in darkness.
- **Sleep disorders:** insomnia, narcolepsy (sudden REM, cataplexy), sleep apnea, somnambulism.
- **Dream theories:** activation-synthesis (brain interprets random activity), Freud's wish fulfillment, problem-solving and cognitive process theories.
- **Hypnosis:** a relaxed state of heightened suggestibility. Dissociation theory sees a split in consciousness; social influence theory sees role-playing. **Meditation:** trained focus of attention; increases alpha and theta activity and lowers stress markers.
- **Drug classes:** depressants (alcohol, barbiturates, benzodiazepines: ↑ GABA), stimulants (amphetamines, cocaine: ↑ dopamine/NE; caffeine, nicotine), opiates/opioids (endorphin receptors), hallucinogens (LSD, psilocybin), marijuana (THC). Reward pathway: ventral tegmental area → nucleus accumbens (mesolimbic dopamine).
- Tolerance (need more for same effect), dependence, and withdrawal are distinct concepts.

Learning

Term	Definition / example
Habituation / dishabituation	Decreased response to repeated stimulus / recovery when stimulus changes
Classical conditioning (Pavlov)	A neutral stimulus paired with an unconditioned stimulus (UCS → UCR) becomes a conditioned stimulus (CS → CR)
Acquisition / extinction / spontaneous recovery	Learning the CS-UCS link / CR fades when CS is presented alone / CR briefly returns after rest
Generalization / discrimination	Responding to similar stimuli / responding only to the specific CS
Operant conditioning (Skinner)	Behavior changes via consequences
Positive / negative reinforcement	Add pleasant / remove aversive stimulus → behavior ↑ (negative reinforcement includes escape and avoidance learning)
Primary / conditioned reinforcers	Innately satisfying (food, water) / valuable through association (money, praise)
Positive / negative punishment	Add aversive / remove pleasant stimulus → behavior ↓
Shaping	Reinforcing successive approximations
Observational learning (Bandura)	Learning by watching models (Bobo doll); involves mirror neurons and vicarious emotion
Latent learning	Learning without reinforcement that appears later (Tolman's rats)

Term	Definition / example
Biological preparedness	Some associations are learned easily (taste aversion after one pairing); others resist training
Instinctive drift	Animals revert to instinctive behaviors despite training

Schedule	Reinforcement given...	Response pattern
Fixed ratio (FR)	After a set number of responses	High rate with post-reinforcement pause
Variable ratio (VR)	After an unpredictable number (slot machines)	Highest rate; most resistant to extinction
Fixed interval (FI)	After a set time	"Scalloped": responding increases near the deadline
Variable interval (VI)	After unpredictable time	Slow, steady rate

Memory

Concept	Details
Encoding types	Visual, acoustic, semantic (deepest, best retained); self-reference effect; mnemonics and chunking aid encoding
Sensory memory	Iconic (visual, <1 s), echoic (auditory, ~3–4 s)
Short-term memory	7 ± 2 items, ~20–30 s without rehearsal
Working memory (Baddeley)	Phonological loop, visuospatial sketchpad, central executive, episodic buffer
Long-term memory	Explicit/declarative (episodic: events; semantic: facts) vs implicit/nondeclarative (procedural skills, priming)
Retrieval	Recall (hardest) < recognition < relearning (savings); emotion can strengthen retrieval (flashbulb memories)
Serial position effect	Primacy (first items → LTM) and recency (last items → STM)
Context and state-dependent memory	Recall is best when context or internal state matches encoding
Spreading activation	Retrieving one concept activates linked nodes in a semantic network (basis of priming)
Forgetting	Decay (Ebbinghaus curve: rapid early loss); proactive interference (old blocks new) vs retroactive (new blocks old); some decline with aging
Amnesia and dysfunction	Anterograde (can't form new memories) vs retrograde (lost prior memories). Alzheimer's disease; Korsakoff's syndrome (thiamine deficiency, often from chronic alcohol use: severe anterograde amnesia with confabulation)
Memory reconstruction	Misinformation effect; source-monitoring errors; false memories
Neural basis	Long-term potentiation (strengthened synapses, glutamate/NMDA); hippocampus consolidates explicit memories; neural plasticity (rewiring, greatest in childhood)

Cognition, Intelligence, and Language

Piaget stage	Age	Hallmarks
Sensorimotor	0–2	Object permanence develops; circular reactions
Preoperational	2–7	Symbolic thinking, egocentrism, centration; lacks conservation
Concrete operational	7–11	Conservation, logical thought about concrete objects
Formal operational	11+	Abstract and hypothetical reasoning

- Schemas are organized frameworks; assimilation fits new info into existing schemas, accommodation changes schemas. Culture and heredity both shape cognitive development (Vygotsky emphasizes culture).
- **Problem-solving:** trial and error, algorithms (guaranteed but slow), heuristics (mental shortcuts), insight. Barriers: mental set, functional fixedness.
- **Heuristics and biases:** availability (judging by ease of recall), representativeness (judging by prototype, ignoring base rates), confirmation bias, belief perseverance, overconfidence, hindsight bias, framing effects.
- **Intelligence:** Spearman's general factor (g); Gardner's multiple intelligences; Sternberg's triarchic theory (analytical, creative, practical); fluid vs crystallized intelligence (crystallized holds up better with age). Both heredity and environment matter.
- **Language components:** phonology (sounds), morphology (word structure), semantics (meaning), syntax (order), pragmatics (context).
- **Language theories:** nativist (Chomsky's language acquisition device; critical period), learning/behaviorist (Skinner; reinforcement), social interactionist (Vygotsky; social interaction drives development). Linguistic relativity (Sapir-Whorf): language shapes thought.
- **Aphasias:** Broca's (expressive; halting speech, comprehension intact), Wernicke's (receptive; fluent but meaningless speech), conduction (can't repeat; arcuate fasciculus).

Studying the Brain

Method	Measures	Strength	Limitation
EEG	Electrical activity through the scalp	Millisecond timing; sleep stages	Poor spatial resolution
fMRI	Blood oxygenation (BOLD) as a proxy for activity	Good spatial resolution, no radiation	Slow (seconds); indirect
PET	Uptake of a radioactive tracer such as labeled glucose	Shows metabolic activity	Requires a tracer; poor timing
CT	X-ray cross-sections	Fast structural images	Radiation; structure only
MRI	Magnetic resonance of tissue	High-resolution structure	Structure only
Lesion and case studies	Behavior after damage	Supports causal links	Damage is uncontrolled; small samples

Lateralization: each hemisphere controls the opposite side of the body. In most people the left hemisphere leads language and analytic tasks; the right leads spatial processing, face recognition, and emotional tone.

Emotion, Motivation, and Stress

Emotion theory	Sequence
James-Lange	Stimulus → physiological arousal → emotion (we feel afraid because we tremble)
Cannon-Bard	Stimulus → arousal and emotion simultaneously (thalamus)
Schachter-Singer (two-factor)	Arousal + cognitive label → emotion
Lazarus (cognitive appraisal)	Appraisal of stimulus → emotion and arousal

- Emotion has three components: cognitive, physiological, and behavioral. Paul Ekman's universal emotions: happiness, sadness, fear, anger, surprise, disgust (plus contempt), recognized cross-culturally via facial expression. Emotions are adaptive: they prepare us to act.
- The limbic system (amygdala, hippocampus, hypothalamus) is central to emotion; the autonomic nervous system produces its physiological signatures (heart rate, skin conductance).
- **Motivation theories:** instinct theory, drive reduction (restore homeostasis via negative feedback), arousal theory (Yerkes–Dodson: moderate arousal optimal; simpler tasks tolerate higher arousal), incentive theory, Maslow's hierarchy (physiological → safety → belonging → esteem → self-actualization), self-determination theory (autonomy, competence, relatedness).
- Biological and sociocultural motivators include hunger, sex drive, and substance addiction. Intrinsic vs extrinsic motivation; **overjustification effect:** extrinsic rewards can undermine intrinsic motivation.
- **Stress:** primary appraisal (is it a threat?) and secondary appraisal (can I cope?). Stressors range from cataclysmic events to daily hassles. Selye's general adaptation syndrome: alarm → resistance → exhaustion. Coping can be problem-focused or emotion-focused; exercise, relaxation, social support, and spirituality all reduce stress responses.

Biological Bases of Behavior and Development

- **Family studies** show traits run in families but cannot separate genes from shared environment. **Twin studies** compare identical (MZ) and fraternal (DZ) twins; higher MZ concordance suggests genetic influence. **Adoption studies** compare children with biological vs adoptive parents.
- **Heritability** is the share of variation in a trait across a population explained by genes. It describes populations, not individuals, and changes when environments change. Genes and environment interact (temperament, epigenetics).
- **Prenatal development:** germinal, embryonic, and fetal stages; teratogens do the most harm during the embryonic stage.
- **Motor development** proceeds head to toe (cephalocaudal) and center outward (proximodistal). Newborn reflexes (rooting, sucking, Moro, Babinski, grasping) fade in the first year.
- **Adolescence:** puberty brings hormonal and physical change; the prefrontal cortex keeps maturing into the mid-20s.

Personality

Perspective	Key ideas and theorists
Psychoanalytic	Freud: id (pleasure principle), ego (reality principle), superego (morality); defense mechanisms; unconscious. Jung (collective unconscious, archetypes), Adler (inferiority complex), Horney
Humanistic	Rogers (unconditional positive regard, congruence of real and ideal self), Maslow (self-actualization)
Trait	Big Five (OCEAN: openness, conscientiousness, extraversion, agreeableness, neuroticism); Eysenck (PEN); Allport (cardinal, central, secondary traits)

Perspective	Key ideas and theorists
Social cognitive	Bandura's reciprocal determinism (behavior, person, environment interact); self-efficacy; locus of control (Rotter)
Behaviorist	Personality is learned through conditioning (Skinner)
Biological	Genetics and temperament shape personality
Situational approach	Behavior depends more on the situation than on stable traits; a challenge to trait theory

Defense mechanism	Example
Repression	Unconsciously pushing away threatening memories
Suppression	Consciously setting thoughts aside
Projection	Attributing one's own unacceptable feelings to others
Displacement	Redirecting emotion to a safer target (kicking the dog after a bad day)
Reaction formation	Acting the opposite of one's feelings
Rationalization	Justifying behavior with acceptable reasons
Regression	Reverting to childlike behavior
Sublimation	Channeling impulses into socially acceptable activity
Denial / intellectualization	Refusing to accept reality / focusing on facts to avoid emotion

Psychological Disorders

Category	Key features
Depressive disorders	Major depressive disorder: ≥ 2 weeks of depressed mood or anhedonia plus other symptoms; persistent depressive disorder (dysthymia): ≥ 2 years. Linked to $\downarrow$ serotonin/NE, HPA overactivity
Bipolar disorders	Bipolar I: at least one manic episode. Bipolar II: hypomania + major depression. Cyclothymia: milder, chronic
Anxiety disorders	Generalized anxiety, specific phobia, social anxiety, panic disorder, agoraphobia
Obsessive-compulsive and related	Obsessions (intrusive thoughts) and compulsions (repetitive behaviors); body dysmorphic disorder
Trauma- and stressor-related	PTSD: intrusion, avoidance, negative mood changes, arousal lasting > 1 month
Schizophrenia spectrum	Positive symptoms (hallucinations, delusions, disorganized speech) vs negative (flat affect, avolition, alogia). Dopamine hypothesis; enlarged ventricles
Dissociative disorders	Dissociative amnesia, dissociative identity disorder, depersonalization/derealization
Somatic symptom disorders	Distress over physical symptoms; conversion disorder (neurological symptoms without organic cause); illness anxiety
Personality disorders	Cluster A (odd: paranoid, schizoid, schizotypal); B (dramatic: antisocial, borderline, histrionic, narcissistic); C (anxious: avoidant, dependent, obsessive-compulsive)
Neurodevelopmental / neurocognitive	ADHD, autism spectrum disorder / Alzheimer's (plaques, tangles, $\downarrow$ ACh), Parkinson's (dopamine loss). Stem cell therapies aim to regenerate lost CNS neurons

Models of illness: biomedical (disease focus) vs biopsychosocial (biological, psychological, and social factors together). The DSM-5 is the diagnostic reference. Depression and anxiety disorders are among the most common disorders.

MNEMONIC

Personality clusters: A = Weird, B = Wild, C = Worried.

Social Psychology

Concept	Definition
Social facilitation	Presence of others improves performance on simple/well-learned tasks, impairs complex ones
Social loafing	Reduced individual effort in groups
Deindividuation	Loss of self-awareness in groups → uninhibited behavior
Bystander effect	Less likely to help when others are present (diffusion of responsibility)
Group polarization	Group discussion pushes views to extremes
Groupthink	Desire for harmony overrides critical thinking
Conformity (Asch)	Yielding to group pressure on line-length judgments; peer pressure is the everyday form
Obedience (Milgram)	Following authority orders to administer "shocks"
Stanford prison study (Zimbardo)	Situational roles strongly shape behavior (methodologically debated)
Compliance techniques	Foot-in-the-door (small then large request), door-in-the-face (large then smaller), lowball, that's-not-all
Attitude components	Cognitive, affective, and behavioral (ABC); behavior can shape attitudes (role-playing effects)
Cognitive dissonance	Discomfort from conflicting beliefs/actions → change attitude or behavior
Elaboration likelihood model	Central route (argument quality; lasting change) vs peripheral route (superficial cues)
Social cognitive theory	Attitudes and behavior change through observation, self-efficacy, and expected outcomes
Fundamental attribution error	Overattributing others' behavior to disposition rather than situation; stronger in individualist than collectivist cultures
Actor-observer bias	Own behavior → situation; others' → disposition
Self-serving bias	Successes → internal; failures → external
Just-world hypothesis	Belief that people get what they deserve
Mere exposure effect	Familiarity increases liking
Prejudice / stereotype / discrimination	Attitude (affective) / cognition / behavior
Stereotype threat	Anxiety about confirming a stereotype impairs performance
Self-fulfilling prophecy	Expectations elicit behavior that confirms them

Concept	Definition
In-group / out-group bias	Favoritism toward one's own group; out-group homogeneity effect
Attribution (Kelley's covariation)	Consistency, distinctiveness, consensus determine internal vs external attribution

Social Interaction and Social Behavior

Topic	What to know
Display rules	Cultural and gender norms for when and how to show emotion; women on average express more and decode nonverbal cues more accurately
Verbal and nonverbal communication	Words vs facial expression, eye contact, gesture, posture, and personal space (proxemics)
Animal signals	Alarm calls, pheromones, the honeybee waggle dance
Attraction	Proximity, similarity, physical attractiveness, mere exposure, reciprocal liking
Aggression	Hostile vs instrumental; frustration-aggression hypothesis; linked to amygdala activity, testosterone, and low serotonin; also learned by observation
Attachment	See Ainsworth and Harlow under Development
Altruism	Kin selection, reciprocal altruism, and the empathy-altruism hypothesis
Social support	Emotional, informational, and tangible support buffer stress and improve health
Foraging behavior	Optimal foraging: animals maximize energy gained per unit of energy and risk spent
Mating and mate choice	Intersexual selection (the sex that invests more is choosier) and intrasexual competition; monogamy, polygyny, polyandry
Game theory	Payoffs depend on others' strategies (prisoner's dilemma, hawk-dove); an evolutionarily stable strategy cannot be beaten by alternatives
Individual vs institutional discrimination	One person's act vs bias built into policies and institutions (redlining). Prejudice does not always produce discrimination (LaPiere's 1934 hotel study)

Development and Identity

Erikson stage (age)	Conflict	Virtue if resolved
Infancy (0-1)	Trust vs mistrust	Hope
Early childhood (1-3)	Autonomy vs shame and doubt	Will
Preschool (3-6)	Initiative vs guilt	Purpose
School age (6-12)	Industry vs inferiority	Competence
Adolescence (12-20)	Identity vs role confusion	Fidelity
Young adulthood (20-40)	Intimacy vs isolation	Love
Middle adulthood (40-65)	Generativity vs stagnation	Care
Late adulthood (65+)	Integrity vs despair	Wisdom

Theorist	Model
Freud (psychosexual)	Oral, anal, phallic (Oedipal/Electra conflict), latency, genital; fixation from unresolved stages
Kohlberg (moral)	Preconventional (avoid punishment, self-interest) → conventional (conformity, law and order) → postconventional (social contract, universal ethics)
Vygotsky	Zone of proximal development: what a learner can do with guidance; culture drives cognitive development
Mead	The "I" (spontaneous self) vs "me" (socialized self); generalized other; role-taking
Cooley	Looking-glass self: we see ourselves as we believe others see us
Ainsworth (strange situation)	Attachment styles: secure, avoidant, ambivalent/resistant, disorganized
Harlow	Infant monkeys preferred a soft cloth mother over a wire mother with food (contact comfort)

- **Self-concept** (who you are), **self-esteem** (how you value yourself), **self-efficacy** (belief you can succeed at a task), **locus of control** (internal vs external).
- **Identity types:** race/ethnicity, gender, age, sexual orientation, class, national. Identity forms through imitation, role-taking, and reference groups that shape self-evaluation.

Classic Experiments and What They Show

P/S passages often describe a famous study without naming it. If you know the setup, you can identify the concept in seconds.

Area	Study	What they did	Finding and MCAT concept
Learning	Pavlov's dogs (around 1900)	Paired a tone with food	Dogs salivated to the tone alone: classical conditioning
Learning	Watson and Rayner, "Little Albert" (1920)	Paired a loud noise with a white rat	Fear generalized to other furry objects: conditioned emotion, stimulus generalization; now a research-ethics example
Learning	Thorndike's puzzle boxes (1898)	Cats escaped boxes over repeated trials	Rewarded actions became faster: law of effect, the basis of operant conditioning
Learning	Skinner box (1930s)	Rats and pigeons pressed levers under different reinforcement rules	Response rates depend on schedule: operant conditioning, shaping
Learning	Garcia and Koelling (1966)	Rats got nausea after taste, light, or sound cues	Taste aversion formed in one trial, even with a delay; light and sound aversions did not: biological preparedness
Learning	Seligman and Maier (1967)	Dogs exposed to inescapable shock	Later failed to escape avoidable shock: learned helplessness, a model of depression
Learning	Tolman (1930)	Rats explored a maze without reward	Ran it fast once food was added: latent learning, cognitive maps
Learning	Bandura's Bobo doll (1961)	Children watched an adult hit a doll	Children imitated the aggression: observational learning, modeling

Area	Study	What they did	Finding and MCAT concept
Memory	Ebbinghaus (1885)	Memorized nonsense syllables and retested himself	Rapid early forgetting that levels off; relearning is faster (savings); spaced practice helps
Memory	Miller (1956)	Reviewed short-term memory span research	About 7 ± 2 items; chunking extends capacity
Memory	Peterson and Peterson (1959)	Blocked rehearsal of letter triads	Recall dropped sharply within about 18 seconds: short-term memory decays without rehearsal
Memory	Sperling (1960)	Flashed letter grids; cued partial report	Most letters were briefly available: iconic memory lasts under a second
Memory	Loftus and Palmer (1974)	Asked how fast cars "smashed" vs "hit"	"Smashed" raised speed estimates and false reports of broken glass: misinformation effect
Biology	Patient H.M. (Scoville and Milner, 1957)	Medial temporal lobes, including hippocampi, removed for epilepsy	Could not form new explicit memories but learned new motor skills: anterograde amnesia; explicit vs implicit memory
Biology	Phineas Gage (1848)	Iron rod passed through frontal lobe	Personality and impulse control changed: frontal lobe and executive function
Biology	Sperry and Gazzaniga split-brain studies (1960s)	Showed images to one hemisphere in patients with a cut corpus callosum	Patients could name left-hemisphere images but not right: lateralization of language
Biology	Hubel and Wiesel (1959)	Recorded single neurons in cat visual cortex	Neurons fired to specific edges and orientations: feature detection
Perception	Gibson and Walk's visual cliff (1960)	Placed infants on glass over an apparent drop	Most crawling infants refused to cross: early depth perception
Emotion	Schachter and Singer (1962)	Injected epinephrine, then exposed people to a euphoric or angry confederate	People labeled the same arousal by context: two-factor theory
Attitudes	Festinger and Carlsmith (1959)	Paid \$1 or \$20 to call a boring task fun	The \$1 group rated the task more enjoyable: cognitive dissonance
Attitudes	Freedman and Fraser (1966)	Asked for a small safe-driving sign, later a large one	Prior small agreement increased compliance: foot-in-the-door
Cognition	Tversky and Kahneman (1981)	Framed the same outcome as lives saved vs lives lost	Choices flipped with framing: framing effect
Social	Triplett (1898)	Cyclists and children reeling line, alone vs together	Faster with others: social facilitation
Social	Ringelmann (1913); Latané and colleagues (1979)	Measured effort alone vs in groups	Individual effort dropped in groups: social loafing
Social	Asch (1951)	Line-length judgments with wrong-answering confederates	About 75% conformed at least once: conformity

Area	Study	What they did	Finding and MCAT concept
Social	Milgram (1963)	Ordered "teachers" to shock a "learner"	65% went to the maximum 450 V: obedience to authority; ethics of deception
Social	Zimbardo's Stanford Prison Experiment (1971)	Assigned students to guard or prisoner roles	Abusive behavior emerged; stopped after 6 days: power of roles (methods widely criticized)
Social	Darley and Latané (1968)	Staged a seizure heard over an intercom	Fewer people helped, and more slowly, as group size grew: bystander effect
Social	Sherif's Robbers Cave (1954)	Split boys into competing camp groups	Hostility formed fast; shared superordinate goals reduced it: in-group/out-group bias
Social	Rosenthal and Jacobson (1968)	Told teachers some students were "bloomers" (chosen at random)	Those students gained more: teacher expectancy, self-fulfilling prophecy
Social	Steele and Aronson (1995)	Framed a test as diagnostic of ability, or not	Black students scored lower when it was framed as diagnostic: stereotype threat
Research	Hawthorne studies (1920s-1930s)	Varied lighting and conditions at a factory	Productivity rose with attention itself: Hawthorne effect
Development	Harlow (1950s)	Infant monkeys with wire vs cloth surrogate mothers	Preferred cloth even without food: contact comfort, attachment
Development	Ainsworth's Strange Situation (1970s)	Mother leaves and returns while the infant is observed	Secure, avoidant, ambivalent (later disorganized) attachment styles
Development	Piaget's conservation tasks	Poured equal water into a taller glass	Preoperational children say the tall glass has more: lack of conservation
Development	Kohlberg's Heinz dilemma	Asked whether a man should steal a drug to save his wife	Reasoning, not the answer, places people in moral stages
Development	Mischel's marshmallow test (1970s)	Children chose one treat now or two later	Delay of gratification; later replications found weaker long-term predictions

SECTION 10

Sociology

Sociology is about 30% of the P/S section. Questions reward precise vocabulary, so learn each term as a definition plus one example.

Theoretical Approaches

Theory	Core idea	Associated thinkers
Functionalism	Society is a system of parts that maintain stability; manifest vs latent functions	Durkheim, Parsons, Merton
Conflict theory	Society is shaped by competition for limited resources and power	Marx, Weber
Symbolic interactionism	Meaning is created through everyday interaction and symbols	Mead, Blumer, Goffman (dramaturgy: front/back stage)
Social constructionism	Reality (e.g., money, gender roles) is jointly constructed and agreed upon	Berger and Luckmann
Rational choice / exchange	Individuals weigh costs and benefits in behavior and relationships	Homans
Feminist theory	Examines gender inequality and power structures	

Microsociology studies face-to-face interaction (symbolic interactionism); **macrosociology** studies large-scale structures and institutions (functionalism, conflict theory).

Culture

- **Elements of culture:** beliefs, values, norms, language, rituals, symbols. Material culture (objects) vs symbolic/nonmaterial culture (values, beliefs, language, norms).
- **Norms:** folkways (informal, mild sanctions), mores (morally significant), taboos (strongly forbidden), laws (formal). Sanctions reward or punish norm-following.
- **Cultural concepts:** ethnocentrism vs cultural relativism; cultural lag (culture trails technology); culture shock; assimilation; multiculturalism; subculture; counterculture; transmission and diffusion; mass media and popular culture.
- **Evolution and culture:** culture can drive genetic change, as when dairying favored lactase persistence.

Social Institutions

Institution	Key concepts
Education	Hidden curriculum (unspoken lessons in conformity); teacher expectancy; educational segregation and stratification
Family	Kinship: consanguineal (blood), affinal (marriage), fictive (chosen). Descent: patrilineal, matrilineal, bilateral. Forms: nuclear, extended; monogamy, polygamy (polygyny, polyandry); marriage and divorce. Family violence: child, elder, and intimate partner abuse

Institution	Key concepts
Religion	Religiosity (strength of religious commitment). Organizations: church (ecclesia), denomination, sect (breakaway group), cult or new religious movement. Religion and change: modernization, secularization, fundamentalism
Government and economy	Weber's types of authority: traditional (custom), charismatic (personal appeal), rational-legal (rules and offices). Economic systems: capitalism, socialism, communism. Political systems: democracy, monarchy, authoritarianism, totalitarianism
Division of labor	Durkheim: mechanical solidarity (traditional societies bound by sameness) vs organic solidarity (modern societies bound by interdependent specialized roles). Anomie is normlessness during rapid change
Health and medicine	Medicalization (social problems redefined as medical); the sick role (Parsons: exempt from duties but obligated to seek care); delivery of health care; illness experience (how people interpret and live with illness, including stigma); social epidemiology (how disease is distributed by social factors)

Socialization

Agents of socialization: family, peers, school, mass media, workplace. Anticipatory socialization prepares people for future roles; resocialization replaces old norms (total institutions such as prisons or the military). Social control keeps behavior within norms through formal and informal sanctions.

Social Structure and Groups

Term	Definition
Status	Social position: ascribed (involuntary), achieved (earned), master status (dominant)
Role	Expected behaviors; role strain (within one role), role conflict (between roles), role exit
Primary / secondary groups	Close, long-term / impersonal, task-oriented
In-group / out-group / reference group	Belongs to / competes with / used for self-comparison
Dyad / triad	Two-member (unstable) / three-member groups
Gemeinschaft / Gesellschaft (Tönnies)	Community based on shared bonds / society based on self-interest
Formal organization and bureaucracy (Weber)	Hierarchy, rules, division of labor, impersonality, merit-based employment
Iron law of oligarchy (Michels)	Organizations tend toward rule by a few
McDonaldization (Ritzer)	Efficiency, calculability, predictability, control spreading through society
Social networks	Strong vs weak ties; weak ties often provide job opportunities

Deviance and Collective Behavior

- **Strain theory (Merton):** deviance arises when people lack legitimate means to reach cultural goals (conformity, innovation, ritualism, retreatism, rebellion).
- **Differential association (Sutherland):** deviance is learned from close others. **Labeling theory:** primary vs secondary deviance; labels become self-identity.

- **Stigma:** extreme disapproval of a person or group. **Collective behavior:** fads, mass hysteria, riots.

Demographic Structure of Society

Characteristic	Key concepts
Age	Aging and the life course; age cohorts share formative experiences (baby boomers); social significance of aging (ageism; activity vs disengagement theories)
Gender	Sex (biological) vs gender (socially constructed); gender segregation separates men and women into different occupations and roles
Race and ethnicity	Race is socially constructed; racialization assigns racial meaning to groups or practices; racial formation (Omi and Winant) describes how racial categories are created and changed through social and political processes
Immigration status	Patterns of immigration; intersects with race and ethnicity and with access to care
Sexual orientation	A demographic characteristic that shapes identity, social experience, and health care access

Demographic Shifts and Social Change

Concept	Definition
Malthusian theory	Population grows geometrically while food grows arithmetically, so famine and disease check growth
Demographic transition	Pre-industrial (high birth and death) → declining death → declining birth → low birth and death
Population pyramids	Expansive (wide base, high fertility), constrictive (narrow base, aging population), stationary (roughly even)
Fertility and mortality rates	Crude birth and death rates are per 1,000 people per year; total fertility rate is average children per woman (replacement ≈ 2.1); age-specific rates count one age group
Migration	Push factors (reasons to leave) vs pull factors (reasons to come)
Social movements	Driven by relative deprivation (discontent from comparison to others, not absolute need); proactive (promote change) vs reactive (resist change); organized through strategies and tactics
Globalization	Driven by communication technology and economic interdependence. World systems theory sorts nations into core, semi-periphery, and periphery; dependency and modernization theories offer competing views. Can produce civil unrest and terrorism as well as growth
Urbanization	Industrialization drew people to cities; suburbanization pulled wealth outward and fed urban decline; gentrification and urban renewal bring higher-income residents back, often displacing lower-income ones

Social Inequality

Concept	Definition
Socioeconomic status (SES)	Combination of income, education, occupation
Class consciousness vs false consciousness (Marx)	Awareness of shared class interests vs adopting beliefs that work against them
Power, privilege, prestige	Ability to act on others; unearned advantages; social respect

Concept	Definition
Social mobility	Vertical (up/down) vs horizontal; intergenerational (across generations) vs intragenerational (within a lifetime)
Meritocracy	Advancement based on ability and effort
Social reproduction	Inequality passed across generations
Cultural / social capital (Bourdieu)	Non-financial assets like education and style / benefits from social networks
Absolute vs relative poverty	Can't meet basic needs vs poor compared with surrounding society
Social exclusion	Segregation and isolation that cut groups off from institutions
Spatial inequality	Residential segregation, neighborhood safety and violence, environmental injustice (hazards near marginalized communities), global inequality
Socioeconomic gradient in health	Health improves at every step up the SES ladder, not only above the poverty line (Whitehall studies of British civil servants)
Health disparities	Differences in health outcomes by race, SES, gender, geography; health care disparities concern access and quality
Intersectionality	Overlapping identities combine to shape experiences of privilege and oppression

SECTION 11

Research Methods and Statistics

Research reasoning appears in every science section, often inside experimental passages. It maps to two AAMC skills: **Reasoning About the Design and Execution of Research** and **Data-Based and Statistical Reasoning** (together about 20% of each science section). Master these concepts once and reuse them everywhere.

Study Design

Term	Definition
Independent / dependent variable	Manipulated or grouping variable / measured outcome
Confounding variable	Related to both IV and DV; creates a spurious association
Control group	Baseline for comparison; positive controls should show an effect, negative controls should not
Randomization / blinding	Random assignment minimizes confounds / hiding assignment from participants (single) or also researchers (double)
Experimental study	Researcher manipulates IV; can establish causation
Cohort study	Follows exposed vs unexposed groups forward to see outcomes
Case-control study	Compares people with vs without an outcome, looking back at exposures
Cross-sectional study	Snapshot of a population at one time
Longitudinal study	Same participants followed over time
Qualitative methods	Ethnography, interviews, focus groups, case studies; rich description, less generalizable
Internal validity	Confidence that the IV caused the DV
External validity	Generalizability to other populations/settings
Reliability	Consistency of a measure (test-retest, inter-rater); a measure can be reliable but not valid
Construct validity	Measures what it claims to measure

- **Biases:** selection bias, sampling bias, attrition, Hawthorne effect (behavior changes when observed), observer/experimenter bias, recall bias, placebo effect, social desirability bias (a risk with self-report measures).
- **Hill's criteria for causation:** strength, consistency, specificity, temporality (the only one that is required), biological gradient (dose-response), plausibility, coherence, experiment, analogy.
- Correlation does not imply causation. Reverse causality and confounds are the two most common alternative explanations.

Research Ethics

- **Belmont Report principles:** respect for persons (informed consent, autonomy), beneficence (maximize benefit, minimize harm), justice (fair distribution of risks and benefits).
- Institutional Review Boards (IRBs) approve human-subjects research. Participants can withdraw anytime. Deception requires justification and debriefing.
- **Equipoise:** genuine uncertainty about which treatment is better justifies a clinical trial.

Statistics

Concept	Definition / rule
Mean, median, mode	Average, middle value, most frequent. Median resists outliers (why income is reported as a median)
Range and interquartile range	Max – min / spread of the middle 50% (Q3 – Q1)
Skew	Right (positive) skew: tail to the right, mean > median. Left (negative): mean < median
Standard deviation	Spread around the mean. Normal distribution: 68% within ± 1 SD, 95% within ± 2 , 99.7% within ± 3
Random vs systematic error	Random error scatters measurements (hurts precision); systematic error shifts them all one way (hurts accuracy)
Null hypothesis (H_0)	No difference or relationship
p-value	Probability of results at least this extreme if H_0 were true; $p < \alpha$ (usually 0.05) → reject H_0
Type I error (α)	False positive: rejecting a true H_0
Type II error (β)	False negative: failing to reject a false H_0
Power ($1 - \beta$)	Probability of detecting a real effect; ↑ with larger sample size and effect size
Confidence interval	Range likely containing the true value; a 95% CI that excludes the null value (0 for differences, 1 for ratios) indicates significance
Correlation (r)	–1 to +1; strength and direction of linear relationship. r^2 = proportion of variance explained
Statistical tests	t-test (2 group means), ANOVA (3+ means), chi-square (categorical frequencies), regression (predict outcome from variables)
Sensitivity / specificity	True positive rate: $TP/(TP + FN)$ / true negative rate: $TN/(TN + FP)$
Positive / negative predictive value	$TP/(TP + FP)$ / $TN/(TN + FN)$; PPV rises with disease prevalence
Statistical vs practical significance	A tiny effect can be statistically significant with a huge sample

Reading Figures and Data

- Before reading the passage text, scan figures: identify axes, units, IV (x-axis), DV (y-axis), and the control condition.
- Error bars: overlapping 95% CI bars suggest (but don't prove) no significant difference; non-overlapping bars suggest a difference.
- Log scales compress large ranges; each tick often represents a 10-fold change.

- Always ask: what did the authors conclude, and does the data actually support it? Many questions test overreach. Longitudinal, cross-sectional, and experimental data each support different kinds of claims.

SECTION 12

CARS Strategy

CARS requires no outside knowledge. Every answer is supported by the passage. Passages are 500–600 words, split evenly between humanities (ethics, philosophy, art, literature, music, religion, studies of diverse cultures) and social sciences (anthropology, economics, history, linguistics, population health, psychology, sociology).

What the AAMC Tests

AAMC skill	Share	Question types it covers
Foundations of Comprehension	30%	Main idea, detail, meaning of a word or phrase in context, tone in a single sentence
Reasoning Within the Text	30%	Function of a detail, author's position across paragraphs, inferences that link distant parts, evaluating an argument's evidence
Reasoning Beyond the Text	40%	Application and analogy; incorporating new information; "which new fact would least change the passage"

The largest share of CARS asks you to take the passage somewhere new, so practice should not stop at finding the main idea.

Timing

Item	Guideline
Passages	9 passages, about 500–600 words each, 5–7 questions per passage
Pace	About 10 minutes per passage: roughly 3–4 minutes reading, 6–7 minutes on questions
Checkpoints	Aim for 3 passages per 30 minutes: about 60 minutes left after passage 3 and 30 minutes left after passage 6
Hard passage	Flag it and move on; return with leftover time. Never leave a question blank (no penalty for guessing)

Reading the Passage

- Read for the author's **main idea**, **purpose** (to argue, explain, critique), and **tone** (neutral, critical, enthusiastic, ambivalent).
- Track whose voice is speaking. Authors often present opposing views before rejecting them.
- Notice pivot words: however, but, yet, nevertheless (contrast); therefore, thus (conclusion); moreover, furthermore (continuation).
- Write a one-sentence summary per paragraph (mentally or on your noteboard) and a one-sentence main idea at the end.
- Don't get stuck on dense sentences or unfamiliar vocabulary; questions rarely hinge on them.

Question Types

Type	What it asks	Approach
Main idea / primary purpose	Author's central thesis	Choose the answer broad enough to cover the whole passage, not one paragraph
Detail / retrieval	What the passage states	Return to the passage and find the line
Inference	What must be true given the text	Pick the answer requiring the smallest leap
Author's attitude / tone	How the author feels about a claim	Look for qualifiers and value-laden words
Function	Why the author included a detail	Ask what role it plays in the argument (example, counterpoint, evidence)
Strengthen / weaken	New info that supports or undercuts an argument	Identify the claim and its evidence first; target the link between them
Application	Apply passage ideas to a new situation	Find the answer the author would most likely endorse
Incorporation of new information	How a new fact affects the argument	Decide whether it supports, contradicts, or is irrelevant

Wrong-Answer Traps

Trap	Description
Extreme language	"Always," "never," "completely," "proves" when the author was measured
Out of scope	Plausible and even true in real life, but not addressed in the passage
Distortion	Twists what the author said, often by exaggeration or partial truth
Opposite	Reverses the author's position
Right answer, wrong question	Accurate statement that doesn't answer what was asked
Faulty use of detail	Pulls a real detail from the wrong context

HIGH-YIELD TIP

Practice CARS daily rather than cramming. After each passage, review every question, including ones you got right, and articulate why each wrong answer is wrong. That habit is the most reliable way to improve.

SECTION 13

Final Weeks and Test Day

Final Four Weeks

- Take official AAMC practice exams, ideally at the same time of day as your scheduled test.
- Review every full-length thoroughly: categorize errors as content gaps, misreading, reasoning mistakes, or timing.
- Revisit this packet's formula and terminology tables every few days rather than learning new material.
- Protect sleep. Sleep consolidates memory (see the sleep table in Section 9).

The Week Of

- Do a trial run to the test center if possible; know parking, travel time, and check-in procedures.
- Taper studying in the last 1–2 days: light review only.
- Confirm ID requirements and appointment details on the AAMC and test-center websites.

Test-Day Checklist

Bring / do	Notes
Valid, government-issued photo ID	Must match registration name exactly
Snacks and water for breaks	Stored in a locker; eat something at each break
Layers of clothing	Testing rooms vary in temperature; rules may restrict items like hooded clothing
Earplugs (provided)	Most centers supply them; practice with them beforehand
Break plan	Use every optional break, even briefly
Mindset reset between sections	Each section is scored separately; don't carry a hard section forward

Last-Minute Rapid Review

Must-know	Quick recall
pH + pOH	14 (25 °C)
Henderson-Hasselbalch	$\text{pH} = \text{pK}_a + \log\left(\frac{[\text{A}^-]}{[\text{HA}]}\right)$
ΔG relationships	$\Delta G = \Delta H - T\Delta S$; $\Delta G^\circ = -RT \ln K = -nFE^\circ$
Ideal gas	$PV = nRT$
Kinematics	$v^2 = v_0^2 + 2a\Delta x$
Energy	$\text{KE} = \frac{1}{2}mv^2$; $\text{PE} = mgh$
Electricity	$V = IR$; $P = IV$
Capacitors	Series: $1/C_{\text{eq}} = \sum 1/C$; parallel: $C_{\text{eq}} = \sum C$

Must-know	Quick recall
Optics	$1/f = 1/o + 1/i$; $m = -i/o$
Fluids	$A_1v_1 = A_2v_2$; $P + \frac{1}{2}\rho v^2 + \rho gh = \text{const}$
Michaelis-Menten	$v = V_{\text{max}}[S]/(K_m + [S])$
Start and stop codons	AUG; UAA, UAG, UGA
Hardy-Weinberg	$p^2 + 2pq + q^2 = 1$
ATP per glucose	$\approx 30\text{--}32$
Cardiac output	$CO = HR \times SV$
Weber's law	$\Delta I/I = \text{constant}$
Type I vs II error	False positive vs false negative

NEXT STEPS

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Recommended Official Resources

- **AAMC "What's on the MCAT Exam?" content outline:** the definitive list of testable topics. This packet follows its structure.
- **AAMC official practice exams, section banks, and question packs:** the closest thing to the real test.
- **Khan Academy MCAT collection:** free video and passage review developed with the AAMC.

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