

Sound & Light (1)

1.1 Miscellaneous

% error = (observed - theoretical) / theoretical * 100%

1.2 Kinematics

x = (a/2)(Δt)^2 + v_0Δt + x_0 v = v_0 + aΔt

v^2 = v_0^2 + 2aΔx Δx = (v_0 + v) / 2 * Δt

1.3 Simple Harmonic Motion

x = A cos(ωt + φ) v = -ωA sin(ωt + φ) a = -ω^2 A cos(ωt + φ)

x_max = A v_max = ωA a_max = ω^2 A F_max = mω^2 A

1.3.1 Springs and Slinkies

x represents the distance from the equilibrium.

If you put a mass on top of the slinky, Δx_eq represents the difference between the original equilibrium and the new equilibrium.

F_s = kx = ma F_s_max = kΔx_eq = 9.8Δm

f = (1/2π)√(k/m) T = 2π√(m/k) ω = 2πf = √(k/m)

SPE = (1/2)kx^2 KE = (1/2)mv^2

TME = (1/2)kx^2 + (1/2)mv^2 = (1/2)kA^2 = (1/2)mv_max^2

1.3.2 Springs in parallel and series

Quantity	In Series	In Parallel
Equivalent spring constant	1/k_eq = 1/k_1 + 1/k_2	k_eq = k_1 + k_2
Deflection (elongation)	x_eq = x_1 + x_2	x_eq = x_1 = x_2
Force	F_eq = F_1 = F_2	F_eq = F_1 + F_2
Stored energy	E_eq = E_1 + E_2	E_eq = E_1 = E_2

1.3.3 Pendulums

f = (1/2π)√(g/L) T = 2π√(L/g)

1.4 Waves

T = 1/f v = λf v = Δx/Δt

1.4.1 Slinkies and strings with fixed ends

F_T = F_s = kx μ = m/L v = √(F_T/μ)

Given mass m_T hanging below a pulley, F_T = m_T g.

1.5 Standing waves

1.5.1 Open-open, closed-closed

n is the number of antinodes, or the n^th harmonic.

f_n = f_1 n = (nv) / 2L f_1 = v / 2L λ_n = 2L / n

1.5.2 Open-closed

f_n = f_1 n = (nv) / 4L f_1 = v / 4L λ_n = 2L / n

1.6 Sound

1.6.1 Speed of sound

v = 331√((T_c + 273) / 273) v ≈ 331 + 0.59T

1.6.2 Sound intensity

I = (Power (W)) / Area = (Power (W)) / (4πr^2)

I_dB = 10 log_10(I / 10^-12) I = 10^(I_dB / 10 - 12)

1.6.3 Doppler effect

[O] → [S] f_o = f_s (v + v_o) / v ← [O] [S] f_o = f_s (v - v_o) / v
[O] ← [S] f_o = f_s (v - v_s) / v [O] [S] → f_o = f_s (v + v_s) / v
[O] → ← [S] f_o = f_s (v + v_o) / (v - v_s) [O] → [S] → f_o = f_s (v + v_o) / (v + v_s)
← [O] ← [S] f_o = f_s (v - v_o) / (v - v_s) ← [O] [S] → f_o = f_s (v - v_o) / (v + v_s)

1.6.4 Constructive and Destructive Interference (2 dimensions)

For a point on the m^th antinodal/nodal line playing the same frequency with the same phase:

PD = mλ

where PD is the path length difference.

1.6.5 Beats

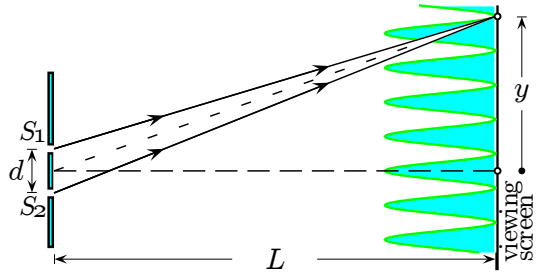
f_B = Δf

1.7 Light

1.7.1 Speed of light

$c = 299\,792\,458 \frac{\text{m}}{\text{s}} \approx 3 * 10^8 \frac{\text{m}}{\text{s}}$

1.7.2 Two-slit experiment



$PD = \frac{dy}{L} = m\lambda$

1.7.3 Mirror

$r = 2f \quad \frac{1}{f} = \frac{1}{p} + \frac{1}{q} \quad M = \frac{h}{h_o} = \frac{-q}{p}$

In a plane mirror, $p = -q$.

1.7.4 Lenses

$\frac{1}{f} = (n - 1)(\frac{1}{r_1} - \frac{1}{r_2}) \quad \frac{1}{f} = \frac{1}{p} + \frac{1}{q} \quad M = \frac{h}{h_o} = \frac{-q}{p}$

Multiple lenses

$p_2 = \Delta x - q_1$

1.7.5 Mirrors and Lenses

Real \iff inverted, virtual \iff upright.

	Converging	Diverging
Mirror		
Lens		
focal length	+	-
object distance	image	image
∞ to $2f$	Real smaller	Virtual smaller
$2f$ to f	Real larger	
f to 0	Virtual larger	
0 to $-f$	Virtual smaller	Virtual larger
$-f$ to $-2f$		Real larger
$-2f$ to $-\infty$		Real smaller

1.7.6 Refraction / Snell’s Law

The **normal line** is the line perpendicular to the surface which touches the intersection of the surface and the light ray.

The **incident angle** is the angle between the ray of light and the normal line.

θ_1 and θ_2 are both measured from the normal line, not the surface.

Refraction occurs when the speed of light in two media are different and light hits the boundary of the two media. The frequency of the light will stay the same, but the speed, wavelength, and direction will change.

$n = \frac{c}{v} \quad n_1 \sin \theta_1 = n_2 \sin \theta_2$

1.7.7 Ray diagrams

Mechanics (2)

2.1 Miscellaneous

% error = (observed − theoretical / theoretical) * 100%

2.2 Kinematics

x(t) = (a/2)t^2 + v_0t + x_0 v(t) = v_0 + at

v^2 = v_0^2 + 2aΔx Δx = (v_0 + v / 2) * Δt

2.3 Forces

F_net = ma

F_T represents tension. It always points in the direction on which the rope pulls on the object.

F_N represents normal force. It takes the direction and magnitude necessary to prevent the object from passing through the surface that creates the normal force.

2.3.1 Friction

f_s ≤ μ_s F_N

The static friction takes the direction and magnitude necessary to prevent the object from moving in the component parallel to the surface, until the magnitude reaches μ_s F_N. Upon reaching μ_s F_N, the static friction is replaced by kinetic friction and the object starts moving:

k_s = μ_k F_N

2.3.2 Centripetal force

The centripetal force always points towards the center of the circle representing the object’s path, and therefore is perpendicular to the velocity. It is just another name for the net force in the centripetal direction. The centripetal acceleration is what causes the object to rotate.

F_c = ma_c = m(v^2 / r) = mrω^2 a_c = v^2 / r

2.4 Work and Energy

W = ∫_a^b F(r) · d r

In one dimension:

W = ∫_a^b F(x)dx

Work-energy theorem. The work is the change in kinetic energy:

W = ΔK

2.5 Simple Harmonic Motion

The object is at rest at the **equilibrium position**. $x = 0$ when the object is at equilibrium, and x represents the distance and direction from the equilibrium. When you pull it to one direction, the **restoring force** pulls the object back toward the equilibrium position. It oscillates back and forth, between $x = -A$ and $x = A$, where A is the **amplitude**. The **period** is the amount of time to complete one oscillation, and the **frequency** is the amount of oscillations that happen in one second (or some other time unit).

x(t) = A cos(ωt + φ)
v(t) = -Aω sin(ωt + φ)
a(t) = -Aω^2 cos(ωt + φ)

2.5.1 Spring force

F_s = -kx
U_s = -½ kx^2

a = -(k/m)x
v = √(k/m(A^2 - x^2))

2.6 Simple Harmonic Motion (old)

x = A cos(ωt+φ) v = -ωA cos(ωt+φ) a = -ω^2 A cos(ωt+φ)
x_max = A v_max = ωA a_max = ω^2 A F_max = mω^2 A

2.6.1 Springs and Slinkies

x represents the distance from the equilibrium.

If you put a mass on top of the slinky, Δx_eq represents the difference between the original equilibrium and the new equilibrium.

F_s = kx = ma F_s_max = kΔx_eq = 9.8Δm
f = (1/2π)√(k/m) T = 2π√(m/k) ω = 2πf = √(k/m)

SPE = ½ kx^2 KE = ½ mv^2
TME = ½ kx^2 + ½ mv^2 = ½ kA^2 = ½ mv_max^2

2.6.2 Springs in parallel and series

Quantity	In Series	In Parallel
Equivalent spring constant	1/k_eq = 1/k_1 + 1/k_2	k_eq = k_1 + k_2
Deflection (elongation)	x_eq = x_1 + x_2	x_eq = x_1 = x_2
Force	F_eq = F_1 = F_2	F_eq = F_1 + F_2
Stored energy	E_eq = E_1 + E_2	E_eq = E_1 + E_2

2.7 Center of mass

The center of mass of an object which consists of masses at discrete points $\vec{r}_1, \vec{r}_2, \vec{r}_3, ..., \vec{r}_n$ is

r_cm = (Σ m_i r_i) / Σ m_i

The center of mass of a solid object with variable density is

r_cm = (∫ r dm) / ∫ dm

To find the velocity of the center of mass, replace \vec{r}_i with \vec{v}_i in the above equations.

2.7.1 Density

3D: density ρ = M/v = dm/dV (kg/m^3)
2D: surface density σ = M/A = dm/dA (kg/m^2)
1D: linear density λ = M/L = dm/dx (kg/m)

2.8 Momentum/Impulse

Definition of Momentum. **Momentum** (\vec{p}) is defined as:

p = mv (Ns = kg m/s)

Definition of Impulse. **Impulse** is the integral of force over time. By the Impulse-Momentum Theorem, it is also the change in momentum.

J = ∫ F dt = Δp = F_net,avg Δt

Additionally,

F_net = dp/dt

Theorem (Conservation of momentum). Momentum is conserved when there are no external forces acting upon the object.

2.9 Rotational motion

2.9.1 Rotational kinematics

θ , angle, is the rotational equivalent of position.

$\Delta\theta$ is called angular displacement.

Angular velocity = $\vec{\omega} = \frac{d\vec{\theta}}{dt} \quad \left(\frac{\text{rad}}{\text{s}}\right)$

Angular acceleration = $\vec{\alpha} = \frac{d\vec{\omega}}{dt} \quad \left(\frac{\text{rad}}{\text{s}^2}\right)$

Arc length = $s = R\theta$

Velocity = $v = R\omega$

Acceleration = $a = R\alpha$

Constant acceleration

$\omega_f = \omega_0 + \alpha t$

$\Delta\theta = \omega_0 t + \frac{1}{2}\alpha t^2$

$\omega_f^2 = \omega_0^2 + 2\alpha\delta\theta$

2.9.2 Torque

$\vec{\tau} = \vec{r} \times \vec{F} \quad |\tau| = |r||F| \sin \theta$

2.9.3 Rotational inertia

Where r represents the distance between the axis of rotation and the object, m represents mass, I represents rotational inertia, and K represents rotational kinetic energy:

$I = mr^2 \quad I_{\text{total}} := \sum m_i r_i^2 = \int r^2 dm \quad K = \frac{1}{2} I \omega^2$

Parallel Axis Theorem. If d is the distance between the axis through the center of mass and the desired axis of rotation parallel to the axis through the center of mass, then the rotational inertia through the desired axis of rotation is

$I_{\text{II}} = I_{\text{cm}} + Md^2$

2.9.4 Newton’s Second Law

$\sum \tau = I\alpha$

2.9.5 Rotational kinetic energy

Definition of Rotational kinetic energy.

$K_{\text{rot}} = \frac{1}{2} I \omega^2$

Definition of Rotational work.

$W = \int \tau d\theta = \Delta K$

2.9.6 Rolling

During rolling, the velocity of the center of mass is

$v_{\text{cm}} = R\omega$

in the direction of rolling. Add $v_{\text{cm}} = R\omega$ to the tangential velocity, $R\omega$ in the direction perpendicular to the radius.

When rolling at the maximum speed possible without slipping, the friction is

$f_s = \mu_s F_N$

Otherwise,

$f_s < \mu_s F_N$

2.9.7 Angular momentum

$\vec{L} = I\vec{\omega}$ for solid objects

$\vec{L} = \vec{r} \times \vec{p}$ for point masses

$L = rp \sin(\theta) = rmv \sin(\theta)$ for point masses

Note: angular velocity’s direction is specified by right-hand rule.

The derivative of angular momentum is the change in external net torque.

$\frac{d\vec{L}}{dt} = \vec{\tau}_{\text{net, ext}}$

2.9.8 Equilibrium

If $\sum F = 0$ and $\sum \tau = 0$, then the object is in equilibrium and therefore is not accelerating.

If $\sum F = 0$ and $\sum \tau \neq 0$, then the object is accelerating in its rotation but has constant velocity.

If $\sum F \neq 0$ and $\sum \tau = 0$, then the object is linearly accelerating but is not accelerating rotationally.

If $\sum F \neq 0$ and $\sum \tau \neq 0$, then the object is in complex motion.

Electromagnetism (3)

3.1 Electrostatics

Definition of Electric charge. A scalar quantity that can describe an object. It can be positive or negative

Definition of Elementary charge (e). The smallest possible charge $e \approx 1.6 * 10^{-19}$ C.

3.1.1 Charging

Procedure (Charging by friction). Rub two nonconductive objects together. The one with the greater electron affinity (electronegativity) becomes negatively charged.

Procedure (Polarization). When two objects near each other, their charge distributions will change in order to ensure that similar charges in the different objects don't get too near each other.

3.1.2 Coulomb's Law

Definition of Coulomb's constant (k).

$$k \approx 8.99 * 10^9 \frac{\text{Nm}^2}{\text{C}^2}$$

Coulomb's Law. If two objects with charges q_1 and q_2 are near each other, then the magnitude of the electrostatic force between the two objects is

$$|F_e| = \frac{k|q_1||q_2|}{r^2}$$

Mathematics (4)

4.1 Logarithms

$\log_b(MN) = \log_b(M) + \log_b(N)$
 $\log_b\left(\frac{M}{N}\right) = \log_b(M) - \log_b(N)$
 $\log_b(M^p) = p \cdot \log_b(M)$
 $\log_b(a) = \frac{\log_x(a)}{\log_x(b)}$
 $\log_b(b) = 1$

4.2 Notation

deg $p(x)$ means the degree of polynomial p .

LC $p(x)$ means the leading coefficient of polynomial p .

4.3 Rational functions

For a rational function $f(x) = \frac{p(x)}{q(x)}$, cancel out any common factors, then:

- For all rational functions:
 - VA: roots of $q(x)$
 - Roots: roots of $p(x)$
- When $\deg p(x) = \deg q(x)$:
 - HA: $y = \frac{\text{LC } p(x)}{\text{LC } q(x)}$
- When $\deg p(x) < \deg q(x)$:
 - HA: $y = 0$
- When $\deg p(x) > \deg q(x)$:
 - HA: none
 - slant asymptote: $\frac{p(x)}{q(x)}$ excluding remainder

4.4 Polynomials

4.4.1 Linear equations

Slope-intercept form: $y = mx + b$
Point-slope form: $y - y_1 = m(x - x_1)$ for point (x, y)
Standard form: $ax + by = c$

4.4.2 Quadratic equations

Standard form: $y = ax^2 + bx + c$
Vertex form: $y = a(x - h)^2 + k$ for vertex (h, k)
Sum of roots: $-\frac{b}{a}$
Product of roots: $\frac{c}{a}$

4.4.3 Higher-degree polynomials

In a polynomial

$a_nx^n + a_{n-1}x^{n-1} + \dots + a_1x + a_0 = 0$

, with roots

$r_1, r_2, r_3, \dots, r_n$

then:

$r_1 + r_2 + r_3 + \dots + r_n = \sum_{k=1}^n nr_k = -\frac{a_{n-1}}{a_n}$

4.5 Sequences and Series

4.5.1 Explicit formulas

Aritmetic sequence: $a_n = a_1 + r(n - 1)$
Geometric sequence: $a_n = a_1 * r^{n-1}$
Harmonic sequence: $a_n = \frac{1}{a_1 + r(n - 1)}$

4.5.2 Arithmetic and Geometric Series

In the following equations, substituting $j = 1$ with $j = 0$, $j - 1$ with j , and a_1 with a_0 will produce the same result.

$\sum_{j=1}^n (a_1 + r(j - 1)) = \frac{n}{2}(2a_1 + (n - 1)d)$

$\sum_{j=1}^n (a_1 * r^{j-1}) = \frac{a_1(1 - r^n)}{1 - r}$

$\sum_{j=1}^\infty (a_1 * r^{j-1}) = \frac{a_1}{1 - r}$ for $r \in [-1, 1]$

4.5.3 Special Sums

$\sum_{j=1}^n c = nc$ $\sum_{j=1}^n ca_j = c \sum_{j=1}^n a_j$
 $\sum_{j=1}^n (a_j + b_j) = \sum_{j=1}^n a_j + \sum_{j=1}^n b_j$ $\sum_{j=1}^n j = \frac{n(n + 1)}{2}$
 $\sum_{j=1}^n j^2 = \frac{n(n + \frac{1}{2})(n + 1)}{3}$ $\sum_{j=1}^n j^3 = \frac{n^2(n + 1)^2}{4}$
 $= \frac{n(2n + 1)(n + 1)}{6}$

4.6 Trigonometry

°	rad	sin	cos	tan
0°	0	0	1	0
30°	$\frac{\pi}{6}$	$\frac{1}{2}$	$\frac{\sqrt{3}}{2}$	$\frac{1}{\sqrt{3}}$
45°	$\frac{\pi}{4}$	$\frac{\sqrt{2}}{2}$	$\frac{\sqrt{2}}{2}$	1
60°	$\frac{\pi}{3}$	$\frac{\sqrt{3}}{2}$	$\frac{1}{2}$	$\sqrt{3}$
90°	$\frac{\pi}{2}$	1	0	undef

4.6.1 Law of Sines and Cosines

$\frac{\sin(A)}{a} = \frac{\sin(B)}{b} = \frac{\sin(C)}{c}$ $c^2 = a^2 + b^2 - 2ab \cos(C)$

4.6.2 Triangle area

$K = \frac{1}{2}bh \qquad K = \frac{1}{2}bc\sin(A) \qquad K = \sqrt{s(s-a)(s-b)(s-c)}$

4.6.3 More identities

$(\sin A)^2 + (\cos A)^2 = 1 \qquad (\tan A)^2 + 1 = (\sec A)^2$
 $\sin(\frac{\pi}{2} - x) = \cos(x) \qquad (\cot A)^2 + 1 = (\csc A)^2$
 $\cos(-x) = \cos(x) \qquad \sin(-x) = -\sin(x) \qquad \tan(-x) = -\tan(x)$

4.6.4 Slope

Where α is the angle between the line and the x-axis, and m is the slope of the line:

$m = \tan \alpha$

4.6.5 Sum and difference formulas

$\sin(A + B) = \sin(A)\cos(B) + \cos(A)\sin(B)$
 $\sin(A - B) = \sin(A)\cos(B) - \cos(A)\sin(B)$
 $\cos(A + B) = \cos(A)\cos(B) - \sin(A)\sin(B)$
 $\cos(A - B) = \cos(A)\cos(B) + \sin(A)\sin(B)$
 $\tan(A + B) = \frac{\tan(A) + \tan(B)}{1 - \tan(A)\tan(B)}$
 $\tan(A - B) = \frac{\tan(A) - \tan(B)}{1 + \tan(A)\tan(B)}$
 $\sin(2A) = 2\sin(A)\cos(A)$
 $\cos(2A) = (\cos A)^2 - (\sin A)^2 = 2(\cos A)^2 - 1 = 1 - 2(\sin A)^2$
 $\tan(2A) = \frac{2\tan(A)}{1 - (\tan A)^2}$

4.7 Vectors

$\vec{v} + \vec{w} = \begin{bmatrix} v_x + w_x \\ v_y + w_y \\ v_z + w_z \end{bmatrix} \qquad c * \vec{v} = \begin{bmatrix} c * v_x \\ c * v_y \\ c * v_z \end{bmatrix}$
 $\vec{v} \cdot \vec{w} = v_xw_x + v_yw_y + v_zw_z = |\vec{v}||\vec{w}|\cos(\theta)$
 $|\vec{v} \times \vec{w}| = |\vec{v}||\vec{w}|\sin(\theta) = \text{area of parallelogram}$
 $\vec{v} \times \vec{w} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ v_x & v_y & v_z \\ w_x & w_y & w_z \end{vmatrix} \qquad \vec{v} \times \vec{w} \perp \vec{v} \qquad \vec{v} \times \vec{w} \perp \vec{w}$
 $\vec{v} \perp \vec{w} \iff \vec{v} \times \vec{w} = \vec{0} \qquad \vec{v} \parallel \vec{w} \iff \vec{v} \cdot \vec{w} = 0$
 $\hat{v} = \frac{\vec{v}}{|\vec{v}|} \qquad \text{proj}_{\vec{b}}\vec{v} = \frac{\vec{v} \cdot \vec{b}}{\vec{b} \cdot \vec{b}} * \vec{b} = (|\vec{v}|\cos(\theta))\hat{b}$

Right-hand rule

To determine the direction of $\vec{v} \times \vec{w}$, put the side of the right hand on \vec{v} and curl the fingers toward \vec{w} . The direction the thumb is pointing is the direction of $\vec{v} \times \vec{w}$.

4.8 Polar

4.8.1 Polar and Cartesian sytems

With point $(x, y) = (r; \theta) = (r; \beta)$, where θ is CCW from the x-axis and β is a bearing, CW from the y-axis:

$x = r\cos(\theta) = r\sin(\beta) \qquad y = r\sin(\theta) = r\cos(\beta)$
 $r = \sqrt{x^2 + y^2} \qquad \theta \equiv \arctan(\frac{y}{x}) \qquad \beta \equiv \arctan(\frac{x}{y})$

4.8.2 Converting functions

Try these substitutions in order:

$x^2 = x^2 + y^2 \qquad \tan \theta = \frac{y}{x} \qquad x = r\cos \theta \qquad y = r\sin \theta$

4.8.3 Limaçons and Petals

The function $y = A\cos(B(\theta + C)) + D$ is equivalent to $y = A\cos(B\theta) + D$ rotated C degrees/radians clockwise.

When C is 0 and B is 1, the x-intercepts are $A \pm D$ and the y-intercepts are $\pm D$, and it forms a limaçon.

When C is 0, but $B \neq 1$, then this sometimes still holds. The x-intercepts may also be $\pm A \pm D$.

There are B petals, with the axis of the first petal on the positive x-axis.

When B is even and $|D| < 1$, then the number of petals is $2B$.

Using sin instead of cos, limaçons have their axes on the positive y-axis, while for petals, the first petal starts from the positive x-axis and curves upwards.

4.9 Complex

$\text{cis}(\theta) = e^{i\theta} = \cos(\theta) + i\sin(\theta)$

To find the n^{th} root of $x_r \text{cis}(x_\theta)$, solve the equation $z_r^n \text{cis}(nx_\theta) = x_r \text{cis}(x_\theta + 360^\circ k)$ for $k \in \mathbb{R}$.

4.10 Function domain

Function	Domain x	Range y
$\log(x)$	$(0, \infty)$	\mathbb{R}
\sqrt{x}	$[0, \infty)$	$[0, \infty)$
$\arcsin(x)$	$[-1, 1]$	$[-\frac{\pi}{2}, \frac{\pi}{2}]$
$\arccos(x)$	$[-1, 1]$	$[0, \pi]$
$\arctan(x)$	\mathbb{R}	$(-\frac{\pi}{2}, \frac{\pi}{2})$

Calculus Theorems (5)

1 Completeness

Theorem (Completeness of the Real Numbers). Every nonempty subset S of \mathbb{R} which is bounded above has a least upper bound $\sup S$.

Definition of Supremum ($\sup S$). A number such that

- (1) $s \leq \sup S$ for every $s \in S$ (which just says that $\sup S$ is an upper bound for S)
- (2) If u is any upper bound for S , then $\sup S \leq u$ (which says that $\sup S$ is the least upper bound for S).

Definition of Infimum ($\inf S$). A number such that

- (1) $\inf S \leq s$ for every $s \in S$ (i.e. $\inf S$ is a lower bound for S)
- (2) If l is any lower bound for S , then $l \leq \inf S$ (i.e. $\inf S$ is the greatest lower bound for S).

Theorem. Every nonempty subset S of \mathbb{R} which is bounded below has a greatest lower bound.

Theorem. If $\min S$ exists, then $\min S = \inf S$.

Theorem. If $A \subset \mathbb{R}$ and $c \geq 0$, and $cA := \{ca : a \in A\}$, $\sup cA = c \sup A$.

Theorem (Rationals between Reals). For every two real numbers a and b with $a < b$, there exists a rational number r satisfying $a < r < b$.

Nested Intervals Theorem.

If $I_n = [a_n, b_n] = \{x \in \mathbb{R} : a_n \leq x \leq b_n\}$ s.t. $a_n \leq a_{n+1}$ and $b_{n+1} \leq b_n$ for $n \in \mathbb{N}$, so that $I_1 \supseteq I_2 \supseteq I_3 \supseteq I_4 \supseteq \dots$, then $\bigcap_{n=1}^\infty I_n \neq \emptyset$.

If $\inf\{b_n - a_n\} = 0$, then $\bigcap_{n=1}^\infty I_n = \{x\}$, where

$x = \sup\{a_n\} = \inf\{b_n\}.$

Capture Theorem. If A is a nonempty subset of \mathbb{R} , then:

- (i) If A is bounded above, then any open interval containing $\sup A$ contains an element of A .
- (ii) Similarly, if A is bounded below, then any open interval containing $\inf A$ contains an element of A .

Theorem (Binary Search (Bisection Method)). If we binary-search for x over $I_1 = [a_1, b_1]$ for $a_1, b_1 \in \mathbb{Q}$, we define I_n s.t. either $I_n := [a_{n-1}, \frac{a_{n-1} + b_{n-1}}{2}]$ or $I_n := [\frac{a_{n-1} + b_{n-1}}{2}, a_{n-1}]$, and we define $a_n := \inf I_n$ and $b_n := \sup I_n$. We define A to be the set of all a_n , and B to be the set of all b_n .

Then, the size of $I_n = \frac{b_1 - a_1}{2^n} = b_n - a_n$, and $\bigcap_{n=1}^\infty I_n \{x\}$, where

$x = \sup\{a_n\} = \inf\{b_n\}.$

2 Limits

Definition of Limit. If $\lim_{x \rightarrow a} f(x) = L$, then for any $\varepsilon > 0$, there exists $\delta > 0$ s.t. for any $x \in (a - \delta, a) \cup (a, a + \delta)$, $f(x) \in (L - \varepsilon, L + \varepsilon)$.

Alternatively,

Definition of Limit. If $\lim_{x \rightarrow a} f(x) = L$, then for any $\varepsilon > 0$, there exists $\delta > 0$ s.t. $|f(x) - L| < \varepsilon$ whenever $0 < |x - a| < \delta$.

Definition of Right-sided limit. If $\lim_{x \rightarrow a^+} f(x) = L$, then for any $\varepsilon > 0$, there exists $\delta > 0$ s.t. $|f(x) - L| < \varepsilon$ whenever $0 < x - a < \delta$.

Definition of Left-sided limit. If $\lim_{x \rightarrow a^-} f(x) = L$, then for any $\varepsilon > 0$, there exists $\delta > 0$ s.t. $|f(x) - L| < \varepsilon$ whenever $0 < a - x < \delta$.

Theorem (Limit Laws). Let $c \in \mathbb{R}$ be a constant and suppose the limits $\lim_{x \rightarrow a} f(x)$ and $\lim_{x \rightarrow a} g(x)$ exist. Then

- $\lim_{x \rightarrow a} (f(x) \pm g(x)) = \lim_{x \rightarrow a} f(x) \pm \lim_{x \rightarrow a} g(x)$
- $\lim_{x \rightarrow a} (cf(x)) = c \lim_{x \rightarrow a} f(x)$
- $\lim_{x \rightarrow a} (f(x)g(x)) = \lim_{x \rightarrow a} f(x) \lim_{x \rightarrow a} g(x)$
- $\lim_{x \rightarrow a} f(x)g(x) = \lim_{x \rightarrow a} f(x) \lim_{x \rightarrow a} g(x)$, provided that $\lim_{x \rightarrow a} g(x) \neq 0$
- $\lim_{x \rightarrow a} x^n = (\lim_{x \rightarrow a} x)^n$
- $\lim_{x \rightarrow a} \frac{a(x)b(x)}{c(x)b(x)} = \lim_{x \rightarrow a} \frac{a(x)}{c(x)}$

These laws also apply to one-sided limits.

Theorem (L'Hopital's Rule). If f and g are differentiable and $g'(x) \neq 0$ on an open interval I that surrounds a , and $\lim_{x \rightarrow a} \frac{f(x)}{g(x)} \in \{\frac{0}{0}, \pm \frac{\infty}{\infty}\}$, then $\lim_{x \rightarrow a} \frac{f(x)}{g(x)} = \lim_{x \rightarrow a} \frac{f'(x)}{g'(x)}$.

Theorem (Composition of Limits). If f is continuous at L and $\lim_{x \rightarrow a} g(x) = L$, then $\lim_{x \rightarrow a} f(g(x)) = f(\lim_{x \rightarrow a} g(x)) = f(L)$

Theorem (Operations on infinity). For $x \in \mathbb{R}$,

$$\infty + x = \infty \qquad -\infty + x = -\infty \qquad \frac{x}{\pm \infty} = 0$$

$$x * \infty = \begin{cases} \infty & \text{if } x > 0 \\ -\infty & \text{if } x < 0 \end{cases}$$

$$x * -\infty = \begin{cases} -\infty & \text{if } x > 0 \\ \infty & \text{if } x < 0. \end{cases}$$

Definition of Indeterminate forms. The following forms are indeterminate and you cannot evaluate them.

$$\frac{0}{0}, \frac{\pm \infty}{\pm \infty}, 0 * \pm \infty, \infty - \infty$$

Squeeze Theorem. Let f , g , and h be defined for all $x \neq a$ over an open interval containing a . If

$$f(x) \leq g(x) \leq h(x)$$

for all $x \neq a$ in an open interval containing a and

$$\lim_{x \rightarrow a} f(x) = L = \lim_{x \rightarrow a} h(x)$$

where $L \in \mathbb{R}$, then $\lim_{x \rightarrow a} g(x) = L$.

3 Continuity

Definition of Continuity at a point. Function f is continuous at point a if $\lim_{x \rightarrow a} f(x) = f(a)$.

Definition. f has a **removable discontinuity** if $\lim_{x \rightarrow a} f(x) = L \in \mathbb{R}$ (in this case either $f(a)$ is undefined, or $f(a)$ is defined by $L \neq f(a)$).

Definition. f has a **jump discontinuity** if $\lim_{x \rightarrow a^-} f(x) = L_1 \in \mathbb{R}$ and $\lim_{x \rightarrow a^+} f(x) = L_2 \in \mathbb{R}$ but $L_1 \neq L_2$.

Definition. f has an **infinite discontinuity** at a if $\lim_{x \rightarrow a^-} f(x) = \pm \infty$ or $\lim_{x \rightarrow a^+} f(x) = \pm \infty$

Intermediate Value Theorem. If f is continuous on $[a, b]$, then for any real number L between $f(a)$ and $f(b)$ there exists at least one $c \in [a, b]$ such that $f(c) = L$. In other words, if f is continuous on $[a, b]$, then the graph must cross the horizontal line $y = L$ at least once between the vertical lines $x = a$ and $x = b$.

Aura Theorem. If $f(x)$ is continuous and $f(a)$ is positive, then there exists an open interval containing a such that for all x in the interval, $f(x)$ is positive.

If $f(x)$ is continuous and $f(a)$ is negative, then there exists an open interval containing a such that for all x in the interval, $f(x)$ is negative.

Bolzano's Theorem. Let f be a continuous function defined on $[a, b]$. If 0 is between $f(a)$ and $f(b)$, then there exists $x \in [a, b]$ such that $f(x) = 0$.

4 Derivatives

The derivative is the instantaneous rate of change, and the slope of the tangent line to the point.

Definition of Derivative ($f'(a)$).

$$\frac{d}{da}f(a) = f'(a) = \lim_{x \rightarrow a} \frac{f(x) - f(a)}{x - a} = \lim_{h \rightarrow 0} \frac{f(a + h) - f(a)}{h}$$

Theorem (Tangent line to a point). The equation of the tangent line to the point $(a, f(a))$ is

$$y = f'(a)(x - a) + f(a)$$

Derivative Rules

Theorem (Difference Rule).

$$\frac{d}{dx}(f(x) - g(x)) = \frac{d}{dx}f(x) - \frac{d}{dx}g(x)$$

Theorem (Sum Rule).

$$\frac{d}{dx}(f(x) + g(x)) = \frac{d}{dx}f(x) + \frac{d}{dx}g(x)$$

Theorem (Constant Multiple Rule).

$$\frac{d}{dx}(cf(x)) = c\frac{d}{dx}f(x)$$

Theorem (Product Rule).

$$\begin{aligned} \frac{d}{dx}(f(x)g(x)) &= f'(x)g(x) + f(x)g'(x) \\ \frac{d}{dx}(f(x)g(x)h(x)) &= f'(x)g(x)h(x) + f(x)g'(x)h(x) \\ &\quad + f(x)g(x)h'(x) \end{aligned}$$

and so on.

Theorem (Quotient Rule).

$$\frac{d}{dx} \frac{f(x)}{g(x)} = \frac{f'(x)g(x) - f(x)g'(x)}{(g(x))^2}$$

Theorem (Power Rule).

$$\frac{d}{dx}x^n = nx^{n-1}$$

for $n \in \mathbb{R}$

Theorem (Chain Rule).

$$\frac{d}{dx}f(g(x)) = f'(g(x))g'(x) \qquad \frac{dy}{dx} = \frac{dy}{db} \frac{db}{dx}$$

Theorem (Derivative of inverse functions). Let $x \in \mathbb{R}$ and f be a differentiable, one-to-one function at x . Then if $f'(x) \neq 0$, then

$$(f^{-1})'(f(x)) = \frac{1}{f'(x)}$$

Theorem (Derivatives of exponentials and logs).

$$\begin{aligned} \frac{d}{dx}e^x &= e^x & \frac{d}{dx}\ln x &= \frac{1}{x} \\ \frac{d}{dx}a^x &= a^x \ln(a) & \frac{d}{dx}\log_a x &= \frac{1}{x \ln(a)} \end{aligned}$$

Theorem (Derivatives of trig functions).

Warning: x must be an angle in radians!

$$\begin{aligned} \sin'(x) &= \cos(x) & \cos'(x) &= -\sin(x) \\ \sec'(x) &= \sec(x)\tan(x) & \csc'(x) &= -\csc(x)\cot(x) \\ \tan'(x) &= \sec(x)^2 & \cot'(x) &= -\csc(x)^2 \\ \arcsin'(x) &= \frac{1}{\sqrt{1-x^2}} & \arccos'(x) &= -\frac{1}{\sqrt{1-x^2}} \\ \operatorname{arcsec}'(x) &= \frac{1}{|x|\sqrt{x^2-1}} & \operatorname{arccsc}'(x) &= -\frac{1}{|x|\sqrt{x^2-1}} \\ \arctan'(x) &= \frac{1}{1+x^2} & \operatorname{arccot}'(x) &= -\frac{1}{1+x^2} \end{aligned}$$

5 Derivative Applications

5.7 Mean Value Theorem

Theorem (Mean Value Theorem). If the function f is continuous on $[a, b]$ and differentiable on (a, b) , then there exists $c \in (a, b)$ s.t.

$$f'(c) = \frac{f(b) - f(a)}{b - a} = \frac{\Delta f(x)}{\Delta x} \text{ on } [a, be]$$

Theorem (Some colloraries to the MVT). If $f(x)$ is differentiable on I , then:

- $f'(x) > 0$ for $x \in I \iff f(x)$ is strictly increasing for $x \in I$.
- $f'(x) \geq 0$ for $x \in I \iff f(x)$ is increasing or constant for $x \in I$.
- $f'(x) = 0$ for $x \in I \iff f(x)$ is constant for $x \in I$.
- $f'(x) \leq 0$ for $x \in I \iff f(x)$ is decreasing or constant for $x \in I$.
- $f'(x) < 0$ for $x \in I \iff f(x)$ is strictly decreasing for $x \in I$.

5.3, 5.10, 5.11, 5.16 Extrema

Definition of Critical point of f . A number c in the domain of f where $f'(c) = 0$ or $f'(c)$ does not exist.

Definition of Stationary point of f . A number c in the domain of f where $f'(c) = 0$

Fermat's Theorem. The local maxima and minima of f are critical points of f .

Exteme Value Theorem. If f is continuous on $[a, b]$, then it has an absolute max and an absolute min.

Theorem (Method to find absolute minima and maxima). Store the critical points of f in the array C . Then, the absolute maximum is $\max\{f(c) : c \in C\}$ and the absolute minimum is $\min\{f(c) : c \in C\}$.

Theorem (First Derivative Test). If f is continuous over I , and $c \in I$ is a critical point of f , and f is differentiable over $I \setminus c$, then:

- If $f'(x)$ is decreasing at c , then $f(c)$ is a local max.
- If $f'(x)$ is increasing at c , then $f(c)$ is a local min.
- If $f'(x)$ has the same sign before and after c , then $f(c)$ is neither a local max nor a local min.

Definition of Concavity. f is concave up on I if the tangent line to f at each point in I is lower than the graph of f .

f is concave down on I if the tangent line to f at each point in I is higher than the graph of f .

Theorem (Test for Concavity). If $f''(x) > 0$ for all $x \in I$, then f is concave up on I .

If $f''(x) < 0$ for all $x \in I$, then f is concave down on I .

Theorem (Second Derivative Test). If f'' is continuous on an interval containing c , where c is the x -value of a stationary point of f . Then,

- If $f''(c) > 0$, then $f(c)$ is a local max.
- If $f''(c) < 0$, then $f(c)$ is a local min.

Trimm's Single Extremum Theorem. If f is continuous on an interval I , and f has a single local extremum (max or min), then that extremum is a global max or min.

Miscellaneous

Definition of Exponential function.

$$\exp x = e^x = \lim_{n \rightarrow \infty} \left(1 + \frac{x}{n}\right)^n$$

6 Integrals
Antiderivative

*Definition of **Antiderivative** / **Indefinite Integral**.* The antiderivative F of a function f is the function such that $F'(x) = f(x)$.

$$F(x) = \int f(x)dx$$

Theorem (Antiderivative plus a constant). If F is the antiderivative of a function f , then $G(x) = F(x) + c$ where $c \in \mathbb{R}$ is also an antiderivative.

*Definition of **Integral**.*

$$(f_1[a,b]) \mapsto \int_a^b f(x)dx \in \mathbb{R}$$

such that the Properties of the Integral are true.

The definite integral takes in a function and a range $[a,b]$, and returns a number. The indefinite integral takes in a function and returns an infinitely large set of functions (the antiderivatives).

If $a > b$, then $\int_a^b f := -\int_b^a f$.

Let $\mathcal{R}([a,b])$ be the set of integrable functions, $\mathcal{C}([a,b])$ be the set of continuous functions, and $\mathcal{B}([a,b])$ be the set of bounded functions on $[a,b]$. Then

$$\mathcal{C}([a,b]) \subset \mathcal{R}([a,b]) \subset \mathcal{B}([a,b])$$

Theorem (Properties of the Integral). The integral is defined such that the following are true:

- (I0) Every continuous function is integrable.
- (I1) If $f(x) = c$, then $\int_a^b f(x)dx = c(b-a)$
- (I2) If $f_1(x) \leq f_2(x)$, then $\int_a^b f_1(x)dx \leq \int_a^b f_2(x)dx$.
- (I3) For any a, b, c , $\int_a^b f(x)dx = \int_a^c f(x)dx + \int_c^b f(x)dx$.

Theorem (Fundamental Theorem of Calculus). Let $f \in \mathcal{R}([a,b])$ be some integrable function, where $a, b \in \mathbb{R}$. Let $\mathcal{F}(x) = \int_a^x f$ for $x \in [a,b]$. Then:

- (a) \mathcal{F} is continuous for every $c \in [a,b]$.
- (b) If f is continuous at $c \in [a,b]$, then \mathcal{F} is diffentiable at c , and $\mathcal{F}'(c) = f(c)$.
- (c) If f is continuous on $[a,b]$, and F is an antiderivative of f , then $\int_a^b f = F(b) - F(a)$, or

$$\int_a^b f(x)dx = F(x)\Big|_a^b = F(b) - F(a)$$

Theorem (Substitution Rule). If g is a function that has a continuous derivative on an interval, another function f is continuous on the range of g , and F is an antiderivative of f on the range of g , then

$$\int f(g(x))g'(x)dx = F(g(x)) + C$$

For $a, b \in \mathbb{R}$,

$$\int_a^b f(g(x))g'(x)dx = \int_{g(a)}^{g(b)} f(u)du = F(g(b)) - F(g(a))$$

Let $u := g(x)$. Then, if $du = E(g'(x)dx)$, where $E \in \mathbb{R}$, then

$$\int Ef(u)du = E \int f(u)du = F(u) + C$$

Theorem (Some Antiderivative Rules).

$$\begin{aligned} \int e^x dx &= e^x + C & \int x^a dx &= \frac{x^{a+1}}{a+1} + C \text{ for } a \neq -1 \\ \int a^x dx &= \frac{a^x}{\ln(a)} + C & \int x^{-1} dx &= \ln|x| + C \end{aligned}$$

$$\int f(x) + g(x)dx = \int f(x)dx + \int g(x)dx$$

Theorem (Integration By Parts). If f and g are integrable functions, then

$$\int f(x)g'(x)dx = f(x)g(x) + \int f(x)g(x)dx$$

Equivalently, if u and v are integrable functions of x , then

$$\int u dv = uv - \int v du$$

Additionally, if f' and g' are continuous, then

$$\int_a^b f(x)g'(x)dx = f(b)g(b) - f(a)g(a) + \int_a^b g(x)f'(x)dx$$

Theorem (Integrals of Trig Functions).

$$\int \sin(x)dx = -\cos(x) + C \quad \int \cos(x)dx = \sin(x) + C$$

$$\int \tan(x)dx = -\ln|\cos(x)| + C = \ln|\sec(x)| + C$$

$$\int \cot(x)dx = \ln|\sin(x)| + C = -\ln|\csc(x)| + C$$

$$\int \sec(x)dx = \ln|\sec(x) + \tan(x)| + C$$

$$\int \csc(x)dx = -\ln|\cot(x) + \csc(x)| + C$$

Procedure (Integrals of Powers of Trig Functions). To solve $\int \sin^n(x) dx$ where n is even, substitute $\sin^2(x) = \frac{1}{2}(1 - \cos(2x))$.

To solve $\int \sin^n(x) dx$ where n is odd, substitute $\sin^2(x) = 1 - \cos^2(x)$ and perform u-sub with $u := \cos^2(x)$ and $du = -\sin(x) dx$.

To solve $\int \cos^n(x) dx$ where n is even, substitute $\cos^2(x) = \frac{1}{2}(1 + \cos(2x))$.

To solve $\int \cos^n(x) dx$ where n is odd, substitute $\cos^2(x) = 1 - \sin^2(x)$ and perform u-sub with $u := \sin^2(x)$ and $du = \cos(x) dx$.

To solve $\int \tan^n(x) dx$, substitute $\tan^2(x) = \sec^2(x) - 1$. If n is odd, perform u-sub with $u := \sec(x)$ and $du = \sec(x) \tan(x) dx$.

To solve $\int \cot^n(x) dx$, substitute $\cot^2(x) = \csc^2(x) - 1$. If n is odd, perform u-sub with $u := \csc(x)$ and $du = -\csc(x) \cot(x) dx$.

To solve $\int \sec^n(x) dx$ where n is even, substitute $\sec^2(x) = \tan^2(x) + 1$, but ensure that $\sec^2(x) dx$ remains. Then perform u-sub with $u := \tan(x)$ and $du = \sec^2(x) dx$.

To solve $\int \sec^n(x) dx$ where n is odd, substitute $\sec^n(x) = \frac{1}{\cos^n(x)} \frac{\cos(x)}{\cos(x)}$. Then substitute $\cos^2(x) = (1+u)(1-u)$ and u-sub with $u := \sin(x)$ and $du = \cos(x)dx$. Then perform partial fraction decomposition.

To solve $\int \csc^n(x) dx$ where n is even, substitute $\csc^2(x) = \csc^2(x) + 1$, but ensure that $\sec^2(x) dx$ remains. Then perform u-sub with $u := \cot(x)$ and $du = -\csc^2(x) dx$.

To solve $\int \csc^n(x) dx$ where n is odd, substitute $\csc^n(x) = \frac{1}{\sin^n(x)} \frac{\sin(x)}{\sin(x)}$. Then substitute $\sin^2(x) = (1+u)(1-u)$ and u-sub with $u := \cos(x)$ and $du = -\sin(x)dx$. Then perform partial fraction decomposition.

Remember that $\int \sec^2(x) dx = \tan(x)$ and $\int \csc^2(x) dx = -\cot(x)$.

Procedure (Trig Substitution).

Orig expression	Substitution	Pythagorean identity
$\sqrt{a^2 - x^2}$	$x := a \sin(\theta)$	$1 - \sin^2(\theta) = \cos^2(\theta)$
$\sqrt{a^2 + x^2}$	$x := a \tan(\theta)$	$1 + \tan^2(\theta) = \sec^2(\theta)$
$\sqrt{x^2 - a^2}$	$x := a \sec(\theta)$	$\sec^2(\theta) - 1 = \tan^2(\theta)$

Partial Fraction Decomposition

Theorem. Any polynomial $Q(x)$ with real coefficients can be factored over the reals as a product of two types of factors:

- linear factors (of the form $ax + b$)
- irreducible quadratic factors (of the form $ax^2 + bxx + c$, where $b^2 - 4ac < 0$)

Definition of Proper rational function. A rational function $\frac{P(x)}{Q(x)}$ where $\deg P < \deg Q$.

Theorem. Any rational function can be converted into a proper rational function plus a polynomial by continually long-dividing by the denominator.

Theorem. Let $R(x) = \frac{P(x)}{Q(x)}$ be a proper rational function, where the denominator $Q(x)$ has been factored into linear and irreducible quadratic factors. $R(x)$ can be written as a sum of partial fractions, where each factor in the denominator gives rise to terms in the partial fraction decomposition:

- For each factor of the form $(ax + b)^k$ in the denominator, add $\sum_{i=1}^k \frac{A_i}{(ax + b)^i}$ to the partial fraction decomposition.
- For each factor of the form $(ax^2 + bx + c)^k$ in the denominator, add $\sum_{i=1}^k \frac{A_ix + B_i}{(ax^2 + bx + c)^i}$ to the partial fraction decomposition.

Riemann Sums

Definition of Elementary function. A function which is a polynomial, rational function, power function (x^a), exponential function (a^x), logarithmic functions, trigonometric and inverse trigonometric functions, or an addition, subtraction, multiplication, division, and composition of the above.

Definition of Riemann sum. Let $f : [a, b] \rightarrow \mathbb{R}$ be any bounded function and let P be a partition of $[a, b]$.

- A choice of a point $x_i^* \in [x_{i-1}, x_i]$ for all $i \in [1, n]$ is called a *tagging* of P , which we denote by $\tau = x_1^*, \dots, x_n^*$.
- A pair (P, τ) is called a *tagged partition*.
- Given a bounded function $f : [a, b] \rightarrow \mathbb{R}$ and a tagged partition (P, τ) of $[a, b]$, the sum

$$R(f, P, \tau) = \sum_{i=1}^n f(x_i^*)(x_i - x_{i-1})$$

is called the *Riemann sum* of f for (P, τ) .

Theorem. If f is integrable on $[a, b]$, then for every $\varepsilon > 0$ there exists $\delta > 0$ s.t. if P is a partition of $[a, b]$ with $|P| := \max x_i - x_{i-1} < \delta$ and $\tau = \{x_i^*\}$, then

$$|R(f, P, \tau) - \int_a^b f(x)dx| < \varepsilon$$

Approximate Integration

Definition of Left-endpoint approximation. Take $x_i^* = x_{i-1} = a + \frac{(i-1)(b-a)}{n}$. Then the left-endpoint approximation of the function $f(x)$ is

$$\int_a^b f(x)dx \approx \sum_{i=1}^n f\left(a + \frac{(i-1)(b-a)}{n}\right) \frac{b-a}{n}$$

The error bound is

$$E_n^L \leq \max\{|f'(x)|\}_{x \in [a, b]} \frac{(b-a)^2}{2n}$$

Definition of Right-endpoint approximation. Take $x_i^* = x_{i-1} = a + \frac{(i)(b-a)}{n}$. Then the right-endpoint approximation of the function $f(x)$ is

$$\int_a^b f(x)dx \approx \sum_{i=1}^n f\left(a + \frac{(i)(b-a)}{n}\right) \frac{b-a}{n}$$

The error bound is

$$E_n^R \leq \max\{|f'(x)|\}_{x \in [a, b]} \frac{(b-a)^2}{2n}$$

Definition of Midpoint approximation. Take $x_i^* = x_{i-1} = a + \frac{(i-\frac{1}{2})(b-a)}{n}$. Then the midpoint approximation of the function $f(x)$ is

$$\int_a^b f(x)dx \approx \sum_{i=1}^n f\left(a + \frac{(i-\frac{1}{2})(b-a)}{n}\right) \frac{b-a}{n}$$

The error bound is

$$E_n^M \leq \max\{|f''(x)|\}_{x \in [a, b]} \frac{(b-a)^3}{24n^2}$$

Definition of Trapezoidal approximation. Then the trapezoidal approximation of the function $f(x)$ is

$$\int_a^b f(x)dx \approx \frac{b-a}{2n} \left(f(a) + 2 \sum_{i=1}^{n-1} f\left(a + \frac{(i)(b-a)}{n}\right) + f(b) \right)$$

The error bound is

$$E_n^T \leq \max\{|f''(x)|\}_{x \in [a, b]} \frac{(b-a)^3}{12n^2}$$

Definition of Simpson's approximation. For even n (greater values of n give more precise more accuracy):

$$\frac{b-a}{3n} \left(f(a) + \sum_{i=1}^{n-1} (3 - (-1)^i) f\left(a + \frac{(i)(b-a)}{n}\right) + f(b) \right)$$

The error bound is

$$E_n^S \leq \max\{|f''''(x)|\}_{x \in [a, b]} \frac{(b-a)^5}{180n^4}$$

8 Integral Applications

Volumes

Generally, if $A(x)$ is the cross-section of a solid that intersects the x -axis at x , then the volume of the solid is

$$V = \int_a^b A(x)dx$$

Theorem (Disk Method). Let $f(x)$ be a continuous, nonnegative function defined on $[a, b]$, and R be the region bounded above by the graph of $f(x)$ and below by the x -axis. Then, the volume of the solid of revolution formed by revolving R around the x -axis is given by

$$V = \int_a^b \pi(f(x))^2 dx$$

Theorem (Washer Method). Let $f(x)$ be a continuous, nonnegative function defined on $[a, b]$, and R be the region bounded above by the graph of $f(x)$ and below by the graph of $g(x)$. Then, the volume of the solid of revolution formed by revolving R around the x -axis is given by

$$V = \int_a^b \pi((f(x))^2 - (g(x))^2) dx$$

Theorem (Cylindrical Shells Method). Let $f(x)$ be a continuous, nonnegative function defined on $[a, b]$, and R be the region bounded above by the graph of $f(x)$ and below by the x -axis. Then, the volume of the solid of revolution formed by revolving R around the y -axis is given by

$$V = \int_a^b 2\pi x f(x) dx$$

Other things

Theorem (Arc length of a curve). The arc length of the curve $f(x)$ on $[a, b]$, when $f'(x)$ exists and is continuous on $[a, b]$, is

$$\int_a^b \sqrt{1 + (f'(x))^2} dx$$

Theorem (Surface area of a solid of revolution). Let $f(x)$ be a continuous, nonnegative function defined on $[a, b]$, and R be the region bounded above by the graph of $f(x)$ and below by the x -axis. Then, the surface area of the solid of revolution formed by revolving R around the x -axis is given by

$$S = \int_a^b 2\pi f(x) \sqrt{1 + (f'(x))^2} dx$$

Theorem (Mass of a thin rod). Let there be a rod whose left end is located at $x = a$ and whose right end is located at $x = b$, and which is on the x -axis. Let $\rho(x)$ be the linear density at the point $x = a$. Then the mass of the rod is

$$M = \int_a^b \rho(x) dx$$

Theorem (Mass of a thin disk). Let there be a disk of radius R whose center is at the origin of the xy -plane. Let the mass be distributed in a rotationally-symmetric way. Let $\rho(r)$ be the radial density at the radius r . Then the mass of the disk is

$$M = \int_0^R 2\pi r \rho(r) dr$$

Theorem (Work). If an object moves along the x -axis from a to b , and $F(x)$ is the force applied to the object when the object is at the point x on the x -axis, then the work is

$$\int_a^b F(x) dx$$

Definition of Average value of a function. If f is continuous on $[a, b]$, then the average value of f on $[a, b]$ is

$$f_{\text{avg}} := \lim_{n \rightarrow \infty} \frac{1}{b-a} \int_a^b f(x) dx$$

Theorem (Mean Value Theorem for Integrals). If f is continuous on $[a, b]$, then there exists $c \in [a, b]$ such that

$$f(c) = f_{\text{avg}} = \frac{1}{b-a} \int_a^b f(x) dx$$

Equivalently,

$$\int_a^b f(x) dx = f(c)(b-a)$$

If f is positive on $[a, b]$, then there is a number c such that the rectangle with base $[a, b]$ and height $f(c)$ has the same area as $\int_a^b f(x) dx$.

9 Improper Integrals

Definition of Improper Integrals with Infinite Bounds.

(a) If $\int_a^t f(x) dx$ exists for every $t \geq a$, then we define

$$\int_a^\infty f(x) dx := \lim_{t \rightarrow \infty} \int_a^t f(x) dx$$

provided that this limit exists and is finite.

(b) If $\int_t^b f(x) dx$ exists for every $t \leq b$, then we define

$$\int_{-\infty}^b f(x) dx := \lim_{t \rightarrow -\infty} \int_t^b f(x) dx$$

provided that this limit exists and is finite.

$\int_a^\infty f(x) dx$ and $\int_{-\infty}^b f(x) dx$ are *convergent* if the corresponding limit exists and *divergent* if the limit doesn't exist.

(c) If both $\int_a^\infty f(x) dx$ and $\int_{-\infty}^b f(x) dx$ are convergent, then we define

$$\begin{aligned} \int_{-\infty}^\infty f(x) dx &= \int_{-\infty}^a f(x) dx + \int_a^\infty f(x) dx \\ &= \lim_{s \rightarrow -\infty} \int_s^a f(x) dx + \lim_{t \rightarrow \infty} \int_a^t f(x) dx \end{aligned}$$

Definition of Improper Integrals with Discontinuous Integrand.

(a) If f is continuous on $[a, b)$ and is discontinuous at b , then define

$$\int_a^b f(x) dx := \lim_{t \rightarrow b^-} \int_a^t f(x) dx$$

provided that this limit exists and is finite.

(b) If f is continuous on $(a, b]$ and is discontinuous at a , then define

$$\int_a^b f(x) dx := \lim_{t \rightarrow a^+} \int_t^b f(x) dx$$

provided that this limit exists and is finite.

$\int_a^\infty f(x) dx$ and $\int_{-\infty}^b f(x) dx$ are *convergent* if the corresponding limit exists and *divergent* if the limit doesn't exist.

(c) If f has a discontinuity at c , where $a < c < b$, and both $\int_a^c f(x) dx$ and $\int_c^b f(x) dx$ are convergent, then we define

$$\begin{aligned} \int_a^b f(x) dx &= \int_a^c f(x) dx + \int_c^b f(x) dx \\ &= \lim_{s \rightarrow c^-} \int_a^s f(x) dx + \lim_{t \rightarrow c^+} \int_t^b f(x) dx \end{aligned}$$

Theorem (Comparison Test). Suppose f and g are continuous functions with $f(x) \geq g(x) \geq 0$ for $x \geq a$.

(a) If $\int_a^\infty f(x) dx$ is convergent, then $\int_a^\infty g(x) dx$ is convergent.

(b) If $\int_a^\infty g(x) dx$ is divergent, then $\int_a^\infty f(x) dx$ is divergent.

Additionally,

(a) If $\int_{-\infty}^b f(x) dx$ is convergent, then $\int_{-\infty}^b g(x) dx$ is convergent.

(b) If $\int_{-\infty}^b g(x) dx$ is divergent, then $\int_{-\infty}^b f(x) dx$ is divergent.

Theorem (Limit Comparison Test). Suppose $f(x)$ and $g(x)$ are positive continuous functions defined on $[a, \infty)$ such that $\lim_{x \rightarrow \infty} \frac{f(x)}{g(x)} = c$ for some positive real number c . Then $\int_a^\infty f(x) dx$ converges iff $\int_a^\infty g(x) dx$.

10 Differential Equations

Definition of Differential equation. An equation involving an unknown function $y = f(x)$ and one or more of its derivatives.

Definition of Solution to a differential equation. A function $y = f(x)$ that satisfies the differential equation when f and its derivatives are substituted into the equation.

Procedure (Euler's Method). To numerically approximate the solution to the differential equation $y' = F(x, y)$ with $y(x_0) = y_0$,

$$y_n = y_{n-1} + F(x_{n-1}, y_{n-1})(x_n - x_{n-1})$$

Definition of Separable Equation. A separable equation is a differential equation where

$$\frac{dy}{dx} = g(x)f(y)$$

for some function $g(x)$ which depends only on x and $f(y)$ which depends only on y .

Theorem. For a separable equation,

$$\int \frac{1}{f(y)} dy = \int g(x) dx$$

Definition of Logistic Differential Equation. For a population P which increases exponentially ($\frac{dP}{dt} \approx kP$) when the population is small compared to the carrying capacity M but where the environment cannot sustain a population larger than M ,

$$\frac{dP}{dt} = kP \left(1 - \frac{P}{M}\right)$$

Then

$$P(t) = \frac{M}{1 + \left(\frac{M}{P_0} - 1\right) e^{-kt}}.$$

and

$$\frac{d^2P}{dt^2} = k^2P \left(1 - \frac{P}{M}\right) \left(1 - \frac{2P}{M}\right)$$

11 Sequences and Series

Definition of Sequence. A **sequence** is an ordered list of real numbers (**elements**) a_1, a_2, a_3, \dots . It can also be considered a function $a : \mathbb{N} \rightarrow \mathbb{R}$.

Definition of Convergence. A sequence converges if $\lim_{n \rightarrow \infty} a_n$ exists.

Theorem. The Limit Laws and Squeeze Theorem also apply to limits of sequences.

Theorem. If $\{a_n\}$ is convergent, then it is bounded.

Theorem (Bounded Monotonic Sequence Theorem).

Every bounded monotonic sequence converges. If $\{a_n\}$ is increasing, then $\lim_{n \rightarrow \infty} a_n = \sup\{a_n : n \geq 1\}$. If $\{a_n\}$ is decreasing, then $\lim_{n \rightarrow \infty} a_n = \inf\{a_n : n \geq 1\}$.

Definition of Series. The **n th partial sum** of $\{a_i\}_{i=1}^n$ is $s_n := \sum_{i=1}^n a_n$. Then the **series** is $\sum_{i=1}^\infty a_i := \lim_{n \rightarrow \infty} s_n$

Theorem (Convergence Test). If the series $\sum_{i=1}^n a_i$ is convergent, then $\lim_{i \rightarrow \infty} a_i = 0$.

Theorem (Divergence Test). If $\lim_{i \rightarrow \infty} a_i \neq 0$, then $\sum_{i=1}^n a_i$ diverges.

Theorem (Integral Test). If f is a continuous positive decreasing function for $x \geq 1$ and $a_n = f(n)$ for $n \in \mathbb{N}$, then

$$\sum_{n=1}^\infty a_n \quad \text{and} \quad \int_1^\infty f(x) \, dx$$

either both converge or both diverge.

Theorem (Remainder Estimate for Integral Test). If f is a continuous positive decreasing function for $x \geq 1$ and $a_n = f(n)$ for $n \in \mathbb{N}$, then

$$\int_{n+1}^\infty f(x)dx \leq R_n = s - s_n = \sum_{i=n+1}^\infty a_i \leq \int_n^\infty f(x)dx$$

and therefore

$$s_n + \int_{n+1}^\infty f(x)dx \leq \sum_{i=1}^\infty a_i \leq s_n + \int_n^\infty f(x)dx$$

Theorem (Comparison Test for Series). If $\sum a_n$ and $\sum b_n$ are series with positive terms:

- If $\sum b_n$ is convergent and $a_n \leq b_n$ for all n , then $\sum a_n$ is also convergent.
- If $\sum b_n$ is divergent and $a_n \geq b_n$ for all n , then $\sum a_n$ is also convergent.

Theorem (Limit Comparison Test for Series). If $\sum a_n$ and $\sum b_n$ are series with positive terms, then

- If $\lim_{n \rightarrow \infty} \frac{a_n}{b_n} \in \mathbb{R}^+$, then either both series converge or both series diverge.
- If $\lim_{n \rightarrow \infty} \frac{a_n}{b_n} = 0$ and $\sum b_n$ converges, then $\sum a_n$ converges.
- If $\lim_{n \rightarrow \infty} \frac{a_n}{b_n} = \infty$ and $\sum b_n$ diverges, then $\sum a_n$ diverges.

Theorem (Well-known series). $\sum \frac{1}{n^p}$ (the **p -series**) converges if $p > 1$ and diverges if $p \leq 1$.

$\sum ar^{n-1}$ (the **geometric series**) converges if $|r| < 1$ and diverges if $|r| \geq 1$. If it converges, $\sum_{n=1}^\infty ar^{n-1} = \frac{a}{1-r}$

Definition of Alternating series. A series $\sum_{n=1}^\infty a_n = \sum_{n=1}^\infty (-1)^n b_n$ or $\sum_{n=1}^\infty (-1)^{n-1} b_n$ where $b_n > 0$.

Theorem (Alternating Series Test). If the alternating series $\sum_{n=1}^\infty (-1)^{n-1} b_n$ satisfies

- (i) $b_{n+1} \leq b_n$ for all n , (i.e. $\{b_n\}$ is decreasing) and
- (ii) $\lim_{n \rightarrow \infty} b_n = 0$,

then the series is convergent.

Theorem (Alternating Series Divergence Test). If $\lim_{n \rightarrow \infty} b_n \neq 0$, then the series is divergent.

Theorem (Alternating Series Estimation Theorem). If $s = \sum_{n=1}^\infty (-1)^{n-1} b_n$ is a series that satisfies the conditions of the Alternating Series Test, then

$$|R_n| := |s - s_n| \leq b_{n+1}$$

and therefore

$$s_n - b_{n+1} \leq s \leq s_n + b_{n+1}$$

Definition of Absolute convergence. A series $\sum_{n=1}^\infty a_n$ **converges absolutely** if the series of absolute values $\sum_{n=1}^\infty |a_n|$ converges.

Definition of Conditional convergence. A series **converges conditionally** if it converges but does not converge absolutely.

Theorem (Rearrangement of terms of absolutely convergent series). The terms of an absolutely convergent series can be rearranged without affecting the value/sum of the series.

Theorem (Absolute convergence implies convergence). If a series converges absolutely, then it converges.

Theorem (Ratio Test).

- If $\lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| < 1$, then the series $\sum_{n=1}^\infty a_n$ converges absolutely and therefore converges.
- If $\lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| > 1$ or $\lim_{n \rightarrow \infty} \frac{a_{n+1}}{a_n} = \infty$, then the series $\sum_{n=1}^\infty a_n$ diverges.
- If $\lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| = 1$, the Ratio Test is inconclusive.

Theorem (Root Test).

- If $\lim_{n \rightarrow \infty} \sqrt[n]{|a_n|} < 1$, then the series $\sum_{n=1}^\infty a_n$ converges absolutely and therefore converges.
- If $\lim_{n \rightarrow \infty} \sqrt[n]{|a_n|} > 1$ or $\lim_{n \rightarrow \infty} \sqrt[n]{|a_n|} = \infty$, then the series $\sum_{n=1}^\infty a_n$ diverges.
- If $\lim_{n \rightarrow \infty} \sqrt[n]{|a_n|} = 1$, the Ratio Test is inconclusive.

12 Power Series

Definition of Power series. A power series centered at a is a series of the form

$$\sum_{k=0}^\infty c_k(x-a)^k = c_0 + c_1(x-a) + c_2(x-a)^2 + \dots$$

where x is a variable, a is a fixed real number called the *center* of the series, and the c_k s are constants called the *coefficients* of the series.

Theorem. For a power series $\sum_{k=0}^\infty c_k(x-a)^k$, there are only three possibilities:

- (i) The series converges only when $x = a$.
- (ii) The series converges for all x .
- (iii) There is a positive number R such that the series converges if $|x-a| < R$ and diverges if $|x-a| > R$. R is called the **radius of convergence**.

Theorem. Suppose $\sum_{n=0}^\infty c_n(x-a)^n$ has radius of convergence $R > 0$. Then $f(x) = \sum_{n=0}^\infty c_n(x-a)^n$ is differentiable (and therefore continuous and integrable) on $(a-R, a+R)$, and

(i) $f'(x) = \sum_{n=0}^\infty \frac{d}{dx} c_n(x-a)^n = \sum_{n=0}^\infty n c_n(x-a)^{n-1}$

(ii) $\int f(x)dx = \sum_{n=0}^\infty \int c_n(x-a)^n = C + \sum_{n=0}^\infty c_n \frac{(x-a)^{n+1}}{n+1}$

Definition of Taylor series. The **Taylor series** of a function f centered at a is

$$\sum_{n=0}^\infty \frac{f^{(n)}(a)}{n!} (x-a)^n$$

Definition of Maclaurin series. The **Maclaurin series** of a function f is the Taylor series of f centered at a :

$$\sum_{n=0}^\infty \frac{f^{(n)}(0)}{n!} x^n$$

Theorem. If f has a power series representation centered at a , then that power series is equivalent to the Taylor series of f centered at a .

Theorem (Basic Maclaurin Series).

$$e^x = \sum_{n=0}^\infty \frac{x^n}{n!} \qquad \text{for } x \in \mathbb{R}$$

$$\sin(x) = \sum_{n=0}^\infty (-1)^n \frac{x^{2n+1}}{(2n+1)!} \qquad \text{for } x \in \mathbb{R}$$

$$\cos(x) = \sum_{n=0}^\infty (-1)^n \frac{x^{2n}}{(2n)!} \qquad \text{for } x \in \mathbb{R}$$

$$\ln(1+x) = \sum_{n=0}^\infty (-1)^n \frac{x^{n+1}}{n+1} \qquad \text{for } |x| < 1$$

$$\arctan(x) = \sum_{n=0}^\infty (-1)^n \frac{x^{2n+1}}{2n+1} \qquad \text{for } |x| < 1$$

$$\frac{1}{1-x} = \sum_{n=0}^\infty x^n \qquad \text{for } |x| < 1$$

$$\frac{1}{(1-x)^2} = \sum_{n=0}^\infty n x^{n-1} = \sum_{n=0}^\infty (n+1) x^n \qquad \text{for } |x| < 1$$

Definition of Taylor polynomial. The n th-degree Taylor polynomial of f at a is

$$\sum_{k=0}^n \frac{f^{(k)}(a)}{k!} (x-a)^k$$

Theorem (Taylor’s Theorem). If f has $(n+1)$ continuous derivatives on an open interval I containing a , then for all x in I ,

$$f(x) = T_n(x) + R_n(x),$$

where T_n is the n th-order Taylor polynomial for f with center a and the remainder is

$$R_n(x) = \frac{f^{(n+1)}(c)}{(n+1)!} (x-a)^{n+1}$$

for some point c between x and a . This form of R_n is also called **Lagrange error bound** or the **Lagrange form of the remainder**.

Theorem. If R_n converges to 0, then

$$f(x) = \sum_{k=0}^n \frac{f^{(k)}(a)}{k!} (x-a)^k.$$

13 Polar

Theorem. If r is a function of θ on the xy -plane, then

$$\frac{dy}{dx} = \frac{\frac{dy}{d\theta}}{\frac{dx}{d\theta}} \qquad \text{and} \qquad \frac{d^2y}{dx^2} = \frac{\frac{d}{d\theta} \left(\frac{dy}{dx} \right)}{\frac{dx}{d\theta}}$$

Theorem (Arc length). If r is a function of θ on the xy -plane, then

$$L = \int_a^b \sqrt{\left(\frac{dx}{d\theta}\right)^2 + \left(\frac{dy}{d\theta}\right)^2} d\theta$$

and therefore

$$L = \int_a^b \sqrt{r^2 + \left(\frac{dr}{d\theta}\right)^2} d\theta$$

14 Vectors

$$\frac{d}{dt} \vec{r}(t) = \begin{pmatrix} x'(t) \\ y'(t) \\ z'(t) \end{pmatrix}$$

$$\int \vec{r}(t)dt = \begin{pmatrix} \int x(t)dt \\ \int y(t)dt \\ \int z(t)dt \end{pmatrix}$$

Multivariable Calculus (6)

Definition of Two-dimensional real-coordinate space (\mathbb{R}^2).

$$\mathbb{R}^2 = \{(x, y) : x, y \in \mathbb{R}\}$$

Definition of Three-dimensional real-coordinate space (\mathbb{R}^3).

$$\mathbb{R}^3 = \{(x, y, z) : x, y, z \in \mathbb{R}\}$$

x, y, z should be presented such that the coordinate system is right-handed ($\hat{k} = \hat{i} \times \hat{j}$ should have direction according to the right-hand rule).

Definition of Standard basis vectors. The standard basis vectors of a space are the unit vectors that go along the axes of the space. All vectors in that space can be expressed as sums of scalar multiples of the standard basis vectors of that space.

The standard basis vectors of \mathbb{R}_2 are \hat{i} and \hat{j} , also called \mathbf{e}_1 and \mathbf{e}_2 .

The standard basis vectors of \mathbb{R}_3 are \hat{i} , \hat{j} , and \hat{k} , also called \mathbf{e}_1 , \mathbf{e}_2 , and \mathbf{e}_3 .

Linear Algebra (7)

1 Linear equations

Let $F = \mathbb{R}$ or $F = \mathbb{C}$.

Definition of Linear equation. An equation that can be written in the form

$$\sum_k a_k x_k = y$$

where all $a_k \in F$ and $y \in F$.

Definition of Solution to a linear equation. The solution to a linear equation is a set $\{s_k\}$ such that $\sum_k a_k s_k = y$, i.e. substituting $x_k = s_k$ results in the equation being true.

Definition of Linear system. A set of linear equations.

Let m be the number of linear equations in the system. Let n be the number of variables in the system. Then the j th equation can be written as

$$\sum_{k=1}^n A_{jk} x_k = y_j$$

Let:

$$A = \begin{bmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & & \vdots \\ A_{m1} & \cdots & A_{mn} \end{bmatrix} \quad X = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} \quad Y = \begin{bmatrix} y_1 \\ \vdots \\ y_m \end{bmatrix}$$

Then the system can be written as $AX = Y$.

Definition of Consistent linear system. A system that has at least one solution.

Definition of Linear combination. The linear combination of the equations of a linear system is a linear equation formed by multiplying each equation by c_j where $c_j \in F$.

This linear combination can be written as

$$\sum_{j=1}^m \sum_{k=1}^n c_j A_{jk} x_k = \sum_{j=1}^m y_j$$

Theorem. All solutions of a linear system are solutions to the linear combination of the equations of the system.

Definition of Equivalent linear systems. Two systems are equivalent if they have the same set of solutions.

Theorem. Two systems are equivalent if each equation in each system is a linear combination of the equations in the other system.

7.0.1 Matrices and rows

Definition of Elementary row operations. The elementary row operations are:

Definition of Scaling. $R_i \mapsto cR_i$ where c is a nonzero scalar.

Definition of Replacement. $R_i \mapsto R_i + cR_j$ where c is a scalar.

Definition of Interchange. Swap R_i and R_j .

Theorem (Elementary row operations are invertible). For any elementary row operation e , there exists an elementary row operation e^{-1} such that $e^{-1}(e(A)) = A$ for any matrix A .

Definition of Row equivalence. Two matrices are row-equivalent if each can be derived from the other using a finite number of elementary row operations.

Definition of Row echelon form (REF). A matrix is in REF if it satisfies:

1. All nonzero rows are above all rows of all zeros.
2. Each leading entry of a row is in a column to the right of the leading entry of the row above it.
3. All entries in a column below a leading entry are zeros.

Definition of Reduced row echelon form (RREF). A matrix is in RREF if it is in REF and additionally satisfies:

4. The leading entry in each nonzero row is 1.
5. Each leading 1 is the only nonzero entry in its column

Definition of Pivot position. A location A_{ij} where $\text{RREF}(A)_{ij}$ is a leading 1.

Definition of Pivot column. A column which contains a pivot position.

Definition of Pivot. A nonzero number at a pivot position.

Procedure (Gauss-Jordan elimination).

Procedure (Gaussian elimination). Iterate through the pivot columns of A from left to right. For each pivot column, use elementary row operations to ensure that the pivot position is nonzero and that all entries in the column below the pivot position are zero. This produces $\text{REF}(A)$.

Procedure (Jordan elimination). Iterate through the pivot columns of $\text{REF}(A)$ from right to left. For each pivot column, use elementary row operations to ensure that all other entries in the column other than the pivot are zero and that the pivot is equal to 1. This produces $\text{RREF}(A)$.

7.0.2 Homogeneous linear systems

Definition of Homogeneous linear system. A system where $y_0 = y_1 = \cdots = y_m = 0$. It can be written as $AX = 0$.

Theorem (Trivial solution). For any homogeneous system, $x_0 = x_1 = \cdots = x_n = 0$ is a solution to the system. Therefore, all homogeneous systems are consistent.

Theorem. (a) If there are less equations than there are variables ($m < n$), then $AX = 0$ has an infinite number of solutions.

(b) If there are an equal number of equations and variables, then A is row-equivalent to the $n \times n$ identity iff $AX = 0$ has only the trivial solution.

(c) If there are more equations than there are variables ($m > n$), then

$$\text{RREF}(A) = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \\ 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

iff $AX = 0$ has only the trivial solution.

Procedure (Solution). To solve a homogeneous system, perform Gauss-Jordan elimination on A so that $R = \text{RREF}(A)$. Then solve $RX = 0$. The variables which are not in pivot columns are free variables and may be set to any value, typically denoted u_1, u_2, \dots

7.0.3 Inhomogeneous linear systems

Procedure (Solution). To solve an inhomogeneous system, perform Gauss-Jordan elimination on $A' = [A|Y]$ so that $R' = [R|Z] = \text{RREF}(A')$. Then solve $RX = Z$. Note that not all inhomogeneous systems are solvable (consistent).