

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)m v\_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/I\_0)      I = 10^(I\_dB/10)

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 - v\_s)      [O] [S] →    f\_o = f\_s v / (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)      ← [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

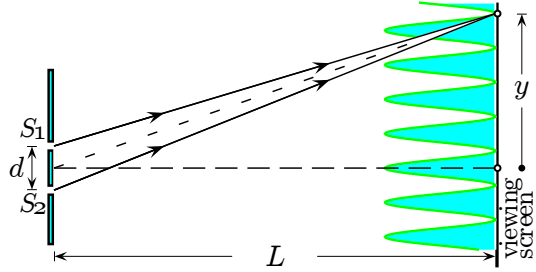
f\_B = Δf

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
$\infty$ 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.

$\theta_1$  and  $\theta_2$  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(r̄) · d r̄

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 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

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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

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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 r̄\_1, r̄\_2, r̄\_3, ..., r̄\_n is

r̄\_cm = (Σ m\_i r̄\_i) / Σ m\_i

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

r̄\_cm = (∫ r̄ dm) / ∫ dm

To find the velocity of the center of mass, replace r̄\_i with v̄\_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 (p̄) is defined as:

p̄ = mv̄      (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.

J̄ = ∫ F̄ dt = Δp = F̄\_net,avg Δt

Additionally,

F̄\_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

$\vec{\theta}$ , 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

$\vec{\tau} = \vec{r} \times \vec{F}$

$|\tau| = |r||F| \sin \theta$

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:

$I = mr^2$

$I_{\text{total}} := \sum m_i r_i^2 = \int r^2 dm$

$K = \frac{1}{2} I \omega^2$

**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.

2.10 Gravitation

Using the equations which are similar to electrostatics:

*Definition of Gravitational constant.*

$G \approx 6.67 * 10^{-11} \frac{\text{Nm}^2}{\text{kg}^2}$

*Definition of Gravitational field.* The vector field  $g$ , which applies to all objects.

The gravitational field points towards masses.

$g$  is also the acceleration caused by gravity.

**Newton’s law of universal gravitation.** If stationary point or spherical masses  $m_1$  and  $m_2$  are near each other but not touching, then the magnitude of the gravitational force between the two objects is

$F_g = -\frac{Gm_1m_2}{r^2}$

The objects are attracted to each other.

**Law.** The gravitational force on a stationary point or spherical mass  $g$  is  $F_g = mg$ , where  $g$  is the strength and direction of the gravitational field.

**Law (by Newton’s law of universal gravitation).** The gravitational field at distance  $r$  due to a stationary point or spherical mass  $m$  is

$g = \frac{Gm}{r^2}.$

The gravitational field at distance  $r$  due to a massive object whose total mass is  $\int dm$  is

$g = \int \frac{G dm}{r^2}$

where  $r$ ’s tail is at the mass and points towards the point for which we want to calculate  $g$ .

2.10.1 Gravitational potential energy

*Definition of Gravitational potential energy.* The gravitational potential energy on  $m_2$  caused by  $m_1$  is

$U_g = -\frac{Gm_1m_2}{r}$

**Theorem (Escape speed).** The minimum speed required for an object to get infinitely far away from the surface of a planet with radius  $R$  and mass  $M$  is

$v = \sqrt{\frac{2GM}{R}}$

This can be found by equating the initial total energy (kinetic and gravitational) to 0.

2.10.2 Orbit

**Theorem.** In circular orbits, the system’s total mechanical energy, the system’s gravitational potential energy, and the satellite’s angular momentum and kinetic energy are constant.

The kinetic energy of the orbiting body is

$$K_g = -\frac{1}{2}U_g$$

and the total energy of the system (orbiting body and massive body) is

$$E_{\text{total}} = \frac{1}{2}U_g = -\frac{GMm}{2r}$$

**Theorem.** In elliptical orbits, the system’s total mechanical energy and the satellite’s angular momentum are constant, but the system’s gravitational potential energy and the satellite’s kinetic energy can each change.

**Kepler’s third law.** The period  $T$  and radius  $R$  of the circular orbit of a satellite around a massive object of mass  $M$  is given by

$$T^2 = \frac{4\pi^2}{GM}R^2$$

2.10.3 Gravitational flux

Note - Newton’s shell theorem is obvious from Gauss’s Law. The AP exam expects you to know Newton’s shell theorem but you can just know Gauss’s Law.

*Definition of Gravitational flux ( $\Phi$ ).* The flux through a surface with area vector  $\vec{A}$  is

$$\Phi = \int \vec{g} \cdot d\vec{A}$$

where  $\vec{g}$  is the gravitational field that passes through the surface, and the area vector’s magnitude is the area and direction is normal/perpendicular to the surface.

*Definition of Net flux.* The flux through any surface that encloses a mass.

**Gauss’s Law.** The net flux is proportional to the enclosed mass, and can be equated to the flux through the surface:

$$\Phi_{\text{net}} = -4\pi GM = \oint \vec{g} \cdot d\vec{A}$$

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 Electric fields

*Definition of Permittivity of free space ( $\epsilon_0$ ).*

$$\epsilon_0 \approx 8.85 * 10^{-12} \frac{C^2}{Nm^2}$$

*Definition of Coulomb's constant (k).*

$$k = \frac{1}{4\pi\epsilon_0} \approx 8.99 * 10^9 \frac{Nm^2}{C^2}$$

**Coulomb's Law.** If stationary point or spherical charges  $q_1$  and  $q_2$  are near each other but not touching, then the magnitude of the electrostatic force between the two objects is

$$|F_e| = \frac{k|q_1||q_2|}{r^2} = \frac{|q_1||q_2|}{4\pi\epsilon_0r^2}$$

*Definition of Electric field.* The vector field  $E$  ( $\frac{N}{C}$ ), which applies to all objects.

The electric field points away from positive charges and towards negative charges.

**Law.** The electrostatic force on a stationary point or spherical charge  $q$  is

$$F_e = Eq$$

where  $E$  is the strength and direction of the electric field.

**Law (by Coulomb's Law).** The electric field at distance  $r$  due to a stationary point or spherical charge  $Q$  is

$$E = \frac{kQ}{r^2} = \frac{Q}{4\pi\epsilon_0r^2}$$

The electric field at distance  $r$  due to a charged object whose total charge is  $\int dq$  is

$$E = \int \frac{k dq}{r^2} = \int \frac{dq}{4\pi\epsilon_0r^2}$$

where  $r$ 's tail is at the charge and points towards the point for which we want to calculate  $E$ .

*Definition of Charge density.*

3D: density	$\rho = \frac{Q}{v} = \frac{dq}{dV}$	$(\frac{C}{m^3})$
2D: surface density	$\sigma = \frac{Q}{A} = \frac{dq}{dA}$	$(\frac{C}{m^2})$
1D: linear density	$\lambda = \frac{Q}{L} = \frac{dq}{dx}$	$(\frac{C}{m})$

**Example (E-field of a sheet of charge).** The magnitude of the E-field caused by a sheet of charge is

$$E = \frac{\sigma}{2\epsilon_0}$$

where the E-field points away from the sheet if the charge is positive, and towards the sheet if the charge is negative.

**Example (E-field of a cylindrical charge).** The magnitude of the E-field caused by a cylindrical charge of radius  $R$  with negligible end effects, at radius  $r$  from its axis, is:

$$\frac{R\sigma}{r\epsilon_0}$$

3.1.3 Electric flux

*Definition of Electric flux ( $\Phi$ ).* The flux through a surface with area vector  $\vec{A}$  is

$$\Phi_E = \int \vec{E} \cdot d\vec{A} \quad \left( \frac{Nm^2}{C} \right)$$

where  $\vec{E}$  is the electric field that passes through the surface, and the area vector's magnitude is the area and direction is normal/perpendicular to the surface.

*Definition of Net flux.* The flux through any surface that encloses a charge.

**Gauss's Law.** The net flux is equivalent to the enclosed charge divided by the permittivity of free space, and can be equated to the flux through the surface:

$$\Phi_{net} = \frac{q}{\epsilon_0} = 4\pi kq = \oint \vec{E} \cdot d\vec{A}$$

3.1.4 Electric potential

*Definition of Electric potential energy.* The work required to move a charge from a reference position to its current location in the electric field.

When the electrostatic force does work  $W_e$  on the object, its electric potential energy decreases and its kinetic energy increases:

$$\Delta U_e = -W_e$$

*Definition of Electric potential.* The work per unit charge required to move a charge from a reference position to its current location in the electric field.

*Definition of Electric potential difference / Voltage.* The difference in electric potential between two points.

$$\Delta V = \frac{\Delta U_e}{q} = -\frac{W_e}{q} = -\int \vec{E}(\vec{r}) \cdot d\vec{r}$$

Therefore,

$$\vec{E} = -\frac{dV}{dr}$$

**Lemma.** If an electric potential  $V$  between two points separated by distance  $L$  is caused by a uniform electric field of strength  $E$ ,

$$V = -EL$$

*Definition of Equipotential line/surface.* A line/surface where for each point on the line/surface, the electric potential is the same.

Graphs of equipotential lines where each line's electric potential is an integer multiple of some number produce a topographic-like map of the electric field, where each of the equipotential lines can be viewed as contour lines.

**Theorem (Potential caused by a point or spherical charge).** The electric potential outside a point or spherical charge, at distance  $r$  from the center of the charge, is

$$\frac{kq}{r}$$

The electric potential inside a spherical charge of radius  $R$  is

$$\frac{kq}{R}$$

(This derives from Coulomb's Law.)

## 3.2 Circuits

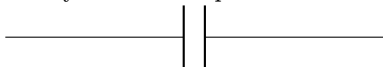
### 3.2.1 Capacitance

**Definition of Capacitor.** At least one charged conductor, usually two.

Common capacitor shapes:

- Parallel plate
- Cylindrical
- Spherical

The symbol for a capacitor is



**Definition of Capacitance.** Where  $Q$  is the magnitude of the charge on one of the plates, and  $V$  is the potential difference between two plates:

$$C = \frac{Q}{V} \quad \left( F = \frac{C}{V} \right)$$

The capacitance remains constant for a given capacitor regardless of any change in charge or voltage; it only depends on the shape of the capacitor.

The capacitance is a positive (unsigned) value.

**Example (Parallel plate capacitor).** The capacitance of a capacitor containing two parallel plates, where each plate has area  $A$  and the distance between the plates is  $d$ , is

$$C = \frac{\epsilon_0 A}{d}$$

**Example (Spherical shell capacitor).** The capacitance of a capacitor containing two concentric spherical shells, where the smaller shell has radius  $a$  and the larger has radius  $b$ , is

$$C = \frac{ab}{bk - ak}$$

**Example (Cylindrical capacitor).** The capacitance of a capacitor containing two concentric cylindrical shells with negligible end effects, where the smaller shell has radius  $a$  and the larger has radius  $b$  and both have length  $L$ , is

$$C = \frac{2\pi\epsilon_0 L}{\ln\left(\frac{b}{a}\right)}$$

**Theorem (Energy stored in a capacitor).**

$$U_e = \frac{1}{2} \frac{Q^2}{C} = \frac{1}{2} VQ = \frac{1}{2} CV^2$$

**Definition of Dielectric.** An object that can be polarized.

**Definition of Permittivity.** The permittivity of space containing a dielectric is equal to

$$K\epsilon_0$$

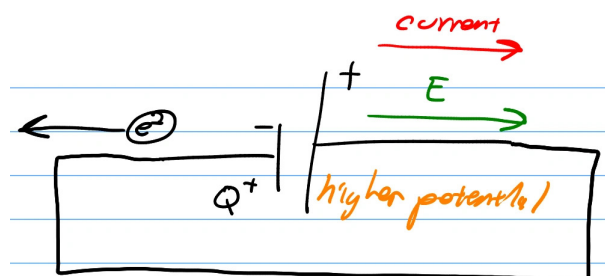
where  $K$  is the dielectric's **dielectric constant**.

### 3.2.2 Miscellaneous circuit stuff

**Definition of Battery.** A battery has two terminals, a positive and a negative terminal. The positive terminal has higher electric potential than the negative terminal, and the battery creates an E-field between the positive and negative terminal. The potential difference between the positive and negative terminal is called the **voltage** of the battery, and is represented as  $\mathcal{E}$ .

The electric field causes positive current to flow from the positive to negative terminal. Equivalently, negative current flows from the negative to positive terminal, which is the way the actual electrons flow.

The symbol for a battery is



### 3.2.3 Loop Law

**Loop Law.** In a circuit, the sum of the signed potential differences along the entire circuit is 0.

$$\sum \Delta V = 0$$

In a circuit with a battery, this means that the voltage (unsigned) of the battery is equal to the sum of the other potential differences along the circuit.

If a set of capacitors were replaced by a single capacitor without changing any of the observable properties of the circuit, then  $C_{eq}$  (the **equivalent capacitance**) is equal to the capacitance of that single capacitor and  $Q_{eq}$  (the **equivalent charge**) is equal to the capacitance of one plate of that single capacitor.

**Example (Capacitors in parallel).**

$$C_{eq} = \sum C_i$$

$$\mathcal{E} = V_1 = \dots = V_n$$

$$Q_{eq} = \sum Q_i$$

**Example (Capacitors in series).**

$$\frac{1}{C_{eq}} = \sum \frac{1}{C_i}$$

$$\mathcal{E} = \sum V_i$$

$$Q_{eq} = Q_1 = \dots = Q_n$$

### 3.2.4 Current and resistance

**Definition of Current / amperage ( $i$  or  $I$ ).** The rate at which charges flow through a conductor.

$$i = I = \frac{dq}{dt} \quad \left( C = \frac{C}{s} \right)$$

**Definition of Junction.** A place in a circuit at which the current can change.

**Law (Junction Rule).** The sum of the current into a junction equals the sum of the current out of the junction.

$$\sum I_{into} = \sum I_{out}$$

**Definition of Current density.**

$$J = \frac{i}{A}$$

**Definition of Resistance ( $R$ ).**

$$R = \frac{V}{i} \quad \left( C = \frac{V}{C} \right)$$

The resistance is a property of the conducting object.

**Ohm's Law.**

$$V = iR$$

**Definition of Resistivity.**

$$\rho = \frac{E}{J} \quad (Cm)$$

The resistivity is a property of the conducting material.

**Lemma.** The resistance of a uniform conductor of length  $L$ , cross-sectional area  $A$ , and resistivity  $\rho$  is

$$R = \frac{\rho L}{A}$$

Law.

$$Q = Nq$$

where  $N$  is the number of charge carriers and  $q$  is the charge of each charge carrier.

If the charge carrier is an electron (as usual), then

$$Q = Ne$$

*Definition of Drift speed.*

$$v_{\text{drift}} = \frac{J}{nq}$$

where  $n = \frac{N}{\text{Volume}}$  (the charge carrier density), and  $q$  is the charge of each charge carrier ( $q = e$  if the charge carrier is an electron).

**Theorem (Power consumed by a resistor).** Most of this energy is converted to heat.

$$P = IV = I^2R = \frac{V^2}{R}$$

**Lemma (Resistors in parallel).** By the Loop Law,

$$V_{eq} = V_1 = \dots = V_n$$

By the Junction Rule,

$$\frac{\mathcal{E}}{R_{eq}} = i_{\text{total}} = \sum i_i$$

Therefore by Ohm's Law,

$$\frac{1}{R_{eq}} = \sum \frac{1}{R_i}$$

**Lemma (Resistors in series).** By the Loop Law,

$$V_{eq} = \sum V_i$$

Therefore by Ohm's Law,

$$R_{eq} = \sum R_i$$

3.2.5 RC circuits

*Definition of RC circuit.* A circuit with a resistor and a capacitor.

*Definition of Time constant.* For an RC circuit,

$$\tau := R_{eq}C_{eq} \quad (\text{s})$$

**Law (Charging a capacitor).** A capacitor can be charged by applying an  $\mathcal{EMF}$  such as a battery on both sides of the capacitor, possibly including a resistor or resistors with equivalent resistance  $R$ .

Initial and final conditions:

$$\begin{array}{ll} t = 0 & t \rightarrow \infty \\ q_0 = 0 & q_{\text{max}} = C\mathcal{E} \\ i_0 = \frac{\mathcal{E}}{R} & i_f = 0 \end{array}$$

Applying the loop law:

$$\mathcal{E} - R\frac{dq}{dt} - \frac{q}{c} = 0$$

Solving the equation, we get:

$$\begin{array}{l} q(t) = q_{\text{max}} \left(1 - e^{-\frac{t}{\tau}}\right) \\ i(t) = i_0 e^{-\frac{t}{\tau}} \end{array}$$

**Law (Discharging a capacitor).** A capacitor can be discharged by shorting both plates, possibly including a resistor or resistors with equivalent resistance  $R$  in between.

Initial and final conditions:

$$\begin{array}{ll} t = 0 & t \rightarrow \infty \\ q_{\text{max}} = C\mathcal{E} & q_f = 0 \\ i_0 = -\frac{\mathcal{E}}{R} & i_f = 0 \end{array}$$

Applying the loop law:

$$-R\frac{dq}{dt} - \frac{q}{c} = 0$$

Solving the equation, we get:

$$\begin{array}{l} q(t) = q_{\text{max}} e^{-\frac{t}{\tau}} \\ i(t) = i_0 e^{-\frac{t}{\tau}} \end{array}$$

(ensure  $i_0 < 0$ )

3.2.6 Magnetism

*Definition of Magnetic field ( $\vec{B}$ ).* The field lines exit through the north pole of the magnet and enter through the south pole of the magnet. They always form a closed loop.

A magnetic field is caused by a moving charged particle, and is perpendicular to the velocity of a particle, as described by the right hand rule - if the velocity  $\vec{v}$  is represented by the right-hand thumb, then curling the rest of the fingers will give the direction of the  $\vec{B}$ -field.

*Definition of Permanent magnet.* A magnet (north and south pole) which stays magnetic without a current or other external force being applied.

It is caused when the electron spins within the magnet are all aligned.

*Definition of Solenoid.* A coiled conducting wire.

If a current is run through the solenoid, it becomes an **electromagnet**.

*Definition of Magnetic force.*

$$\vec{F}_B = q\vec{v} \times \vec{B}$$

therefore

$$|F_B| = q|v||B|\sin\theta$$

**Lemma (Magnetic force on a straight wire).** Given a wire of length  $l$  (define  $\vec{l}$  to be the vector whose magnitude is the length of the wire and whose direction is the direction of the current), with current  $i$  passing through it, in a uniform external magnetic field  $\vec{B}_{\text{ext}}$ ,

$$\vec{F}_B = i\vec{l} \times \vec{B}_{\text{ext}}$$

*Definition of Permeability of free space.*

$$\mu_0 = 4\pi * 10^{-7} \quad \frac{\text{Tm}^2}{\text{C}}$$

**Biot-Savart Law.** The B-field at point  $P$  caused by a point current part of a longer current-carrying object is

$$d\vec{B} = \frac{\mu_0 i}{4\pi} \frac{d\vec{s} \times \hat{r}}{r^2}$$

where  $d\vec{s}$  is the length of the point current and  $\hat{r}$  is the unit vector of the vector from the point current to  $P$ .

**Ampère's Law.** The B-field along an Amperian loop (a closed loop) is related to the enclosed current by

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 i_{\text{enc}}$$



where  $d\vec{s}$  represents the length of a infinitesimally small segment of the Amperian loop and  $i_{\text{enc}}$  represents the current enclosed by the Amperian loop. ( $\vec{B}$  is measured at each point along the Amperian loop.)

**Example (B-field due to a straight wire).** The B-field due to a straight wire carrying current  $i$ , measured at a distance  $r$  from the center of the wire, is

$$B = \frac{\mu_0 i}{2\pi r}$$

Within the straight wire with a radius of  $R$ , at a distance  $r$  from the center of the wire,

$$B = \frac{\mu_0 i r}{2\pi R^2}$$

**Example (B-field inside a solenoid).** The B-field along the central axis inside a solenoid with  $n$  loops of wire per unit length carrying current  $i$ , is

$$B_0 = \mu_0 n i$$

3.2.7 Magnetic flux

*Definition of Magnetic flux.* The flux through a surface with area vector  $\vec{A}$  is

$$\Phi_B = \int \vec{B} \cdot d\vec{A} \quad (\text{W} = \text{Tm}^2)$$

where  $\vec{B}$  is the  $B$ -field that passes through the surface, and the area vector's magnitude is the area and direction is normal/perpendicular to the surface.

**Faraday's Law.** The emf induced by a changing magnetic flux through the surface through a closed conductive loop is

$$\mathcal{E} = -N \frac{d\Phi_B}{dt}$$

**Lenz's Law.** The direction of the induced emf (and thus the induced current) is such that the induced magnetic field it produces opposes the change in the magnetic flux that caused it.

**Theorem (by Lenz's Law).** An increasing magnetic flux induces a  $B$ -field in the opposite direction of the changing flux.

An decreasing magnetic flux induces a  $B$ -field in the same direction as the changing flux.

The induced current's direction is determined by the induced  $B$ -field using the right-hand rule.

3.2.8 Inductors

*Definition.* A device which stores energy in a magnetic field, based on the current flowing through it.

*Definition of Inductance.* The inductance of an inductor with  $N$  loops, with current  $I$  flowing through it, and where  $\Phi_B$  is the flux through the surface bounded by one loop of the inductor:

$$L = \frac{N\Phi_B}{I} \quad \left( \text{H} \frac{\text{Tm}^2}{\text{C}} \right)$$

**Theorem (Inductance of a solenoidal inductor).** The inductance of a solenoid with  $n$  loops of wire per unit length, of length  $l$ , where  $A$  is the area of the surface bounded by one loop of the solenoid, is

$$L = \mu_0 n^2 A l$$

**Theorem (Constitutive equation).** The EMF induced by an inductor is given by

$$\mathcal{E} = -L \frac{di}{dt}$$

The direction is specified by Lenz's Law.

**Theorem (Energy stored in an inductor).** The energy stored in an inductor is

$$U_L = \frac{1}{2} L I^2$$

3.2.9 RL circuits

*Definition of RL circuit.* A circuit with a resistor and an inductor.

*Definition of Inductive time constant.* For an RL circuit,

$$\tau_L := \frac{L}{R} \quad (\text{s})$$

**Theorem (Behavior of an RL circuit with a battery).** By the Loop Law,

$$\mathcal{E} - IR - L \frac{di}{dt} = 0$$

Solving the diffeq, we get

$$I(t) = \frac{\mathcal{E}}{R} \left( 1 - e^{-\frac{t}{\tau_L}} \right)$$

The circuit starts off with no current, and as time goes on the current increases until it reaches its final value  $I = \frac{\mathcal{E}}{R}$  at which point the inductor stores its max energy.

**Theorem (Behavior of an RL circuit after the battery is disconnected).** By the Loop Law,

$$-IR - L \frac{di}{dt} = 0$$

Solving the diffeq, we get

$$I(t) = \frac{\mathcal{E}}{R} e^{-\frac{t}{\tau_L}}$$

The circuit starts off with current of  $I = \frac{\mathcal{E}}{R}$  and ends with no current, at which point the inductor stores no energy.

3.2.10 LC circuits

*Definition of LC circuit.* A circuit with an inductor and a capacitor.

This circuit stores energy. At some times the capacitor stores energy, but the capacitor discharges into the inductor until the inductor stores all the energy. Then the inductor releases energy towards the capacitor, causing the capacitor to store all the energy but with the positive and negative side swapped.

**Theorem.**

$$\omega = \frac{1}{\sqrt{LC}} \quad f = \frac{1}{2\pi\sqrt{LC}}$$

The charge and current on one plate of the capacitor is given by

$$q(t) = Q \cos(\omega t) \quad i(t) = q'(t) = -Q\omega \sin(\omega t)$$

where  $Q$  is the maximum charge on one plate of the capacitor.

The energy in the LC circuit is:

$$U_{\text{total}} = \frac{1}{2} \frac{Q^2}{C} = U_e + U_L = \frac{1}{2} \frac{q^2}{C} + \frac{1}{2} L i^2$$

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:

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

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

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



# 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  $\lim_{x \rightarrow a} \frac{f(x)}{g(x)} \in \left\{\frac{0}{0}, \pm \frac{\infty}{\infty}\right\}$ , 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  $x \in \mathbb{R}$ ,

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

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

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

**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

$$\lim_{x \rightarrow a^-} f(x) = \pm \infty \text{ or } \lim_{x \rightarrow a^+} f(x) = \pm \infty$$

**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!

$$\begin{aligned} \sin'(x) &= \cos(x) & \cos'(x) &= -\sin(x) \\ \sec'(x) &= \sec(x)\tan(x) & \csc'(x) &= -\csc(x)\cot(x) \\ \tan'(x) &= \sec(x)^2 & \cot'(x) &= -\csc(x)^2 \end{aligned}$$

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

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.

Theorem (Single local extremum is global extremum of continuous function). 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  $(ax^2 + bxx + c)^k$  in the denominator, add  $\sum_{i=1}^k \frac{A_i x + B_i}{(ax^2 + bxx + c)^i}$  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  $(P, \tau)$  is called a *tagged partition*.
- Given a bounded function  $f : [a, b] \rightarrow \mathbb{R}$  and a tagged partition  $(P, \tau)$  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  $(P, \tau)$ .

**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

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

**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

$$N(y) \frac{dy}{dx} = M(x)$$

for some function  $M(x)$  which depends only on  $x$  and  $N(y)$  which depends only on  $y$ .

**Theorem.** For a separable equation,

$$\int N(y) \frac{dy}{dx} dx = \int M(x) dx$$

and therefore

$$\int N(y) dy = \int M(x) dx$$



**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

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

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:

- The series converges only when  $x = a$ .
- The series converges for all  $x$ .
- 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**. The behavior at  $|x-a| = R$  is not defined.

**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

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

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

**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).**

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

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

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

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

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

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

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

**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  $\theta$  on the  $xy$ -plane, then

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

**Theorem (Arc length).** If  $r$  is a function of  $\theta$  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

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

**Theorem.** The area of a region bounded by a function  $r = R(\theta)$  between  $\theta = \alpha$  and  $\theta = \beta$  is

$$\frac{1}{2} \int_{\alpha}^{\beta} r^2 d\theta$$

This can be derived using MVC by evaluating

$$\int_{\alpha}^{\beta} \int_0^r r dr d\theta$$

### 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)

Colley (2012) refers to *Vector Calculus, Fourth Edition* by Susan Jane Colley.

6.1 Vectors, lines, planes

6.1.1  $\mathbb{R}^n$

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  $\mathbf{e}_3$ .

6.1.2 Vectors

See the properties of fields in the LinAlg notes for definitions of addition and scalar multiplication.

Definition of Displacement vector. The vector from the end of  $\vec{A}$  to the end of  $\vec{B}$  when their starts are in the same location.

$$\overrightarrow{AB} = \vec{B} - \vec{A}$$

6.1.3 Dot and cross products

Definition of Dot product. Where  $a, b \in \mathbb{R}^n$  and  $\theta$  is the angle between  $a$  and  $b$ :

$$a \cdot b = \sum a_i b_i = |a||b| \cos \theta$$

Theorem (Properties of dot product). For  $\vec{a}, \vec{b}, \vec{c} \in \mathbb{R}^n$  and  $k \in \mathbb{R}$ :

- $\vec{a} \cdot \vec{a} = |\vec{a}|^2$
- $\vec{a} \cdot \vec{a} = 0$  iff  $\vec{a} = 0$
- Commutativity:  $\vec{a} \cdot \vec{b} = \vec{b} \cdot \vec{a}$
- Distributivity:  $\vec{a} \cdot (\vec{b} + \vec{c}) = \vec{a} \cdot \vec{b} + \vec{a} \cdot \vec{c}$
- Distributivity:  $(k\vec{a}) \cdot \vec{b} = k(\vec{a} \cdot \vec{b}) = \vec{a} \cdot (k\vec{b})$

- $\vec{a} \cdot \vec{b} = 0$  iff  $a \perp b$ ,  $a = 0$ , or  $b = 0$ .

Definition of Cross product. For  $\vec{a}, \vec{b} \in \mathbb{R}^3$ , the unique vector  $a \times b$  satisfying

- $|a \times b|$  is the area of the parallelogram spanned by  $a$  and  $b$
- $a \times b = 0$  iff  $a \parallel b$ ,  $a = 0$ , or  $b = 0$ .
- $a \times b$  is orthogonal to  $a$  and  $b$ .
- $(a, b, a \times b)$  is right-handed (if the coordinate system is right-handed)

Theorem (Properties of cross product). For  $a, b, c \in \mathbb{R}^3$  and  $k \in \mathbb{R}$ :

- $a \times b = (-b) \times a$
- $a \times (b + c) = a \times b + a \times c$
- $(a + b) \times c = a \times c + b \times c$
- $k(a \times b) = (ka) \times b = a \times (kb)$

Theorem (Calculation of cross product). Where  $a, b \in \mathbb{R}^n$  and  $\theta$  is the angle between  $a$  and  $b$ :

$$a \times b = \begin{bmatrix} a_2 b_3 - a_3 b_2 \\ a_3 b_1 - a_1 b_3 \\ a_1 b_2 - a_2 b_1 \end{bmatrix} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \end{vmatrix}$$
$$= \hat{i} \begin{vmatrix} a_2 & a_3 \\ b_2 & b_3 \end{vmatrix} + \hat{j} \begin{vmatrix} a_1 & a_3 \\ b_1 & b_3 \end{vmatrix} + \hat{k} \begin{vmatrix} a_1 & a_2 \\ b_1 & b_2 \end{vmatrix}$$
$$|a \times b| = |a||b| \sin \theta$$

6.1.4 Lines

The most useful notation for a line is in parametric form:

Definition of Parametric form of a line. Where  $r_0 \in \mathbb{R}^3$  is a point on the line, and  $t \in \mathbb{R}^3$ :

$$r(t) = r_0 + vt$$

$t$  is called the direction vector.

Theorem. Two lines are parallel iff their direction vectors are scalar multiples of each other.

Definition of Skew lines. Two lines are skew iff they do not intersect but are not parallel, i.e. they lie in different parallel planes.

Procedure (Finding the intersection of two lines). Given lines with parametric equations

$$r_1(t) = a_1 + v_1 t \quad r_2(t) = a_2 + v_2 t$$

solve the system of equations

$$a_1 + v_1 t_1 = a_2 + v_2 t_2$$

for  $t_1$  or  $t_2$ , then plug it in to the appropriate equation.

(Break up the equation into its  $x$ ,  $y$ , and  $z$  components, or whichever is appropriate for your coordinate space.)

6.1.5 Planes

Colley [1.5]

Definition of Plane. A plane  $\Pi$  is determined uniquely by a point  $P$  in the plane and a normal vector  $n$ .

A plane is the set of points  $A$  in space such that  $\vec{AP}$  is perpendicular to  $n$ .

Theorem (Scalar equation for a plane in  $\mathbb{R}^3$ ). If  $n \in \mathbb{R}^3$  is the normal vector to the plane (vector perpendicular to the plane), and  $P \in \mathbb{R}^3$  is a point on the plane:

$$n_x(x - P_x) + n_y(y - P_y) + n_z(z - P_z) = 0$$

or equivalently:

$$n_x x + n_y y + n_z z = n_x P_x + n_y P_y + n_z P_z$$

Procedure (Equation of plane containing three points). If  $A, B, C \in \mathbb{R}^3$  are points on our plane, then we can find the normal vector by performing  $n = \overrightarrow{AB} \times \overrightarrow{AC} = (B - A) \times (C - A)$  (since  $\overrightarrow{AB}$  and  $\overrightarrow{AC}$  are vectors on the plane).

Theorem (Parametric equation for a plane in  $\mathbb{R}^3$ ). If  $a, b \in \mathbb{R}^3$  are nonparallel nonzero vectors on the plane, and  $P \in \mathbb{R}^3$  is a point on the plane, then the parametric equation for the plane is:

$$x(s, t) = P + sa + tb$$

6.1.6 Distance

Colley [1.5]

Procedure (Distance between point and line). Let  $P$  be the point, and  $A + Lt$  be the line. Then the distance is

$$|\overrightarrow{AP} - \text{proj}_L \overrightarrow{AP}| = \vec{P}$$

Procedure (Distance between parallel planes). Let  $\Pi_1$  and  $\Pi_2$  be the two planes.

If  $n$  is normal to both planes, and  $P_1 \in \Pi_1$  and  $P_2 \in \Pi_2$ , then the answer is

$$|\text{proj}_n \overrightarrow{P_1 P_2}|$$

6.1.7 Cylindrical and spherical coordinates

Colley [1.7] Trimm [5.6, 5.7]  
Brummet [08, MVCWUP:Feb3(29-33)]

*Definition of Cylindrical coordinate.* An ordered pair  $(r, \theta, z)$  where  $r$  is the distance between the point and the  $z$ -axis,  $\theta$  is the angle counterclockwise from the positive  $x$ -axis along the  $xy$ -plane, and  $z$  is the position on the  $z$ -axis.

*Definition of Spherical coordinate.* An ordered pair  $(\rho, \phi, \theta)$ , where  $\rho$  is the distance between the point and the origin,  $\phi$  is the angle clockwise from the positive  $z$ -axis going downwards towards the  $xy$ -plane, and  $\theta$  is the angle counterclockwise from the positive  $x$ -axis along the  $xy$ -plane.

Typically we use the following restrictions:

$$\rho > 0 \qquad 0 \leq \theta \leq 2\pi \qquad 0 \leq \phi \leq \pi$$

**Theorem (Useful formulas).**

$$\begin{aligned} r &= \rho \sin \phi & z &= \rho \cos \phi \\ x &= \rho \sin \phi \cos \theta & y &= \rho \sin \phi \sin \theta \\ r^2 &= x^2 + y^2 & x &= r \cos \theta & y &= r \sin \theta \end{aligned}$$

6.2 Functions, limits, differentiation

6.2.1 Multivariable functions

Colley [2.1] Trimm [3.1, 3.2] Brummet [MVCWUP:Feb4(35-41)]

*Definition of Function.* All functions  $f : X \rightarrow Y$  are defined by:

- A domain set  $X$
- A codomain set  $Y$
- A rule of assignment that associates a unique element  $y \in Y$  to each element  $x \in X$

*Definition of Graph.* The graph of  $f : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$  is the set

$$\{(x_1, \dots, x_n, f(x)) : x = (x_1, \dots, x_n)\}$$

Specifically, for  $f : \mathbb{R}^2 \rightarrow \mathbb{R}$  the graph is the set

$$\{(x, y, z) : (x, y) \in X \text{ and } z = f(x, y)\}$$

*Definition of Level set.* Let  $f : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$ . The **level set at height  $c$  of  $f$**  is the set in  $\mathbb{R}^n$  defined by the equation  $f(\vec{a}) = c$ , where  $c$  is a constant. This is equivalent to the set

$$\{\vec{x} \in \mathbb{R}^n : f(\vec{x}) = c\}$$

In  $\mathbb{R}^2$ , this is also called a **level curve**.

*Definition of Contour set.* Let  $f : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$ . The **contour set at height  $c$  of  $f$**  is the set in  $\mathbb{R}^{n+1}$  defined by the two equations  $z = f(\vec{a})$  and  $z = c$ , where  $c$  is a constant. This is equivalent to the set

$$\{\vec{x} \in \mathbb{R}^{n+1} : z = f(\vec{x}) = c\}$$

If  $f : X \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}$ , this is also called a **contour curve**. It is equivalent to the level curve, except it is located in  $\mathbb{R}^3$  rather than  $\mathbb{R}^2$ .

6.2.2 Limits

Trimm [3.3, DiffEq-1.0] Brummet [09, MVCWUP:Feb11(42-46)]  
Colley [2.2]

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

*Definition of Continuity.* Let  $f : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$  and let  $\vec{a} \in X$ . Then  $f$  is continuous at point  $\vec{a}$  iff

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

If  $f$  is continuous at all  $\vec{a} \in X$ , then we say that  $f$  is continuous.

6.2.3 Differentiation

Colley [2.3, 2.4]  
Trimm [3.4, DiffEq-1.0]  
Brummet [11, 12.5, MVCWUP:Feb12/22(48-54)]

*Definition of Partial derivative with respect to  $x$ .* The partial derivative of  $f(x, y)$  with respect to  $x$  is

$$\lim_{h \rightarrow 0} \frac{f(a + h, b) - f(a, b)}{h}$$

Let  $z = f(x, y)$ . Then the partial derivative is denoted by

$$f_x(x, y) = f_x = \frac{\partial f}{\partial x} = \frac{\partial}{\partial x} f(x, y) = \frac{\partial z}{\partial x} = D_x f$$

*Definition of Partial derivative.* The partial derivative of  $f(\vec{x})$  with respect to the  $i$ th variable is

$$\frac{\partial f(\vec{x})}{\partial x_i} = \lim_{h \rightarrow 0} \frac{f\left(\begin{bmatrix} x_0 \\ \vdots \\ x_i + h \\ \vdots \\ x_n \end{bmatrix}\right) - f(\vec{x})}{h}$$

This is equivalent to letting  $F(x_i) = f(\vec{x})$  and finding  $F'(x_i)$ .

*Definition of Higher-order partial.* The result of taking the partial derivative of a partial derivative, which may be higher-order.

A partial derivative that is not higher-order is called a **first-order partial**. A partial derivative of a first-order partial is a second-order partial, a partial derivative of a second-order partial is a third-order partial, etc.

A higher-order partial which is the result of taking the partial with respect to  $x_1$ , then with respect to  $x_2$ , then with respect to  $x_3, \dots, x_n$ , is denoted by

$$f_{x_1 \cdots x_n} = \frac{\partial}{\partial x_n} \cdots \frac{\partial}{\partial x_1} f$$

$x_1 \cdots x_n$  do not have to be distinct. If  $x_1 \cdots x_n$  are not all the same then the higher-order partial is called a **mixed partial derivative**.

*Definition of  $C^k$  function.* Where  $k$  is a nonnegative integer, a function  $f : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$  is of order  $C^k$  at point  $\vec{x} \in X$  iff its  $k$ -th order and lower partials exist and are continuous at  $\vec{x}$ .

It is of order  $C^\infty$  at point  $\vec{x}$  iff it is of order  $C^k$  at  $\vec{x}$  for all  $k \in \mathbb{N}$ .

It is of order  $C^k$  iff it is of order  $C^k$  at all  $x \in \vec{x}$ .

**Theorem.** Let  $f : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$  whose  $k$ -th order and lower partials exist and are continuous on  $X$ . Then its  $k$ -th order and lower partials may be evaluated in any order, i.e.

$$f_{x_1 \cdots x_n} = f_{x_n \cdots x_1} = f_{x_1 x_3 x_2 7 \cdots x_4} = \cdots$$

*Definition of Gradient.*

$$\nabla f(\vec{x}) = \begin{bmatrix} \frac{\partial f(x)}{\partial x_1} \\ \vdots \\ \frac{\partial f(x)}{\partial x_n} \end{bmatrix}$$

6.2.4 Implicit surfaces

Brummet [12]

*Definition of Implicit surface.* A surface in  $\mathbb{R}^3$  defined by an equation which is not solved for  $x, y$ , nor  $z$ .

We often express it as

$$F(x, y, z) = 0,$$

in which case the surface is the set of points which satisfy  $F(x, y, z) = 0$ .

**Theorem.** The gradient  $\nabla F(\vec{x})$  is the normal vector to the tangent plane to the implicit surface defined by  $F(\vec{x}) = k$ , where  $k$  is a constant.

Equivalently, if  $x_0$  is a point on the level set  $S = \{x \in X : F(x) = k\}$  where  $F : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$ , then the vector  $\nabla F(x_0)$  is perpendicular to  $S$ .

6.2.5 Chain rule

Colley [2.5] Trimm [3.8, 6.5, DiffEq-1.0]  
Brummet [12, MVCWUP:Feb24(58-61)]

*Definition of Jacobian.* If  $f : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$  is a vector-valued function, then the Jacobian is

$$Df \left( \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \right) = \begin{bmatrix} \nabla f_1 \\ \nabla f_2 \\ \vdots \\ \nabla f_m \end{bmatrix} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \cdots & \frac{\partial f_2}{\partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_m}{\partial x_1} & \frac{\partial f_m}{\partial x_2} & \cdots & \frac{\partial f_m}{\partial x_n} \end{bmatrix}$$

**Theorem (Multivariable chain rule).** Suppose  $X \subseteq \mathbb{R}^m$  and  $T \subseteq \mathbb{R}^n$  are open and  $f : X \rightarrow \mathbb{R}^p$  and  $r : T \rightarrow \mathbb{R}^m$  are defined so that  $T \subseteq X$ . If  $x$  is differentiable at  $t_0 \in T$  and  $f$  is differentiable at  $x_0 = r(t_0)$ , then the composite  $f \circ r$  is differentiable at  $t_0$ , and we have

$$(f \circ r)'(t) = \nabla f(x_0) \cdot r'(t_0)$$

Equivalently,

$$D(f \circ r)(t_0) = Df(x_0)Dr(t_0)$$

In  $\mathbb{R}^3$ ,

$$\frac{dF}{dt} = \frac{\partial F}{\partial x} \frac{dx}{dt} + \frac{\partial F}{\partial y} \frac{dy}{dt} + \frac{\partial F}{\partial z} \frac{dz}{dt}$$

6.2.6 Paths

Brummet [MVCWUP:Feb24(55-56)]

*Definition of Path.* A path in  $\mathbb{R}^n$  is a function  $x : I \rightarrow \mathbb{R}^n$ , where  $I$  is a set of scalars. If  $I = [a, b]$ , then the endpoints of the path are  $f(a)$  and  $f(b)$ .

*Definition of Tangent vector.* Given a path  $r : \mathbb{R} \rightarrow \mathbb{R}^3$ , the tangent vector to said path at some point  $P$  is given by  $r'(t)$ , provided that  $r'(t) \neq 0$ . In  $\mathbb{R}^3$ ,

$$r'(t) = \lim_{h \rightarrow 0} \frac{r(t+h) - r(t)}{h} = \begin{bmatrix} \frac{dx}{dt} \\ \frac{dy}{dt} \\ \frac{dz}{dt} \end{bmatrix}$$

*Definition of Derivative of vector-valued function.* Let  $f : T \subseteq \mathbb{R} \rightarrow \mathbb{R}^m$ . Then

$$f'(t) = \begin{bmatrix} f'_1(t) \\ f'_2(t) \\ \vdots \\ f'_m(t) \end{bmatrix}$$

6.2.7 Differentiability

Colley [2.3] Trimm [3.5] Brummet [13.5]

*Definition of Linear approximation* ( $\mathbb{R}^n \rightarrow \mathbb{R}$ ). The **linear approximation** or **tangent plane** ( $\mathbb{R}^3$ ) or **hyperplane** to the graph of a function  $f$  at the point  $\vec{a}$  is expressed by

$$L(\vec{x}) = f(\vec{a}) + \nabla f(\vec{a}) \cdot (\vec{x} - \vec{a})$$

In  $\mathbb{R}^3$ , this is equivalent to the plane

$$z = L(x, y) = f(a, b) + f_x(a, b)(x - a) + f_y(a, b)(y - b)$$

*Definition of Linear approximation* ( $\mathbb{R}^n \rightarrow \mathbb{R}^m$ ). The **linear approximation** to a vector-valued function  $f$  at the point  $\vec{a}$  is expressed by

$$L(\vec{x}) = f(\vec{a}) + Df(\vec{a})(\vec{x} - \vec{a})$$

*Definition of Differentiability.* Let  $f : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$ , where  $X$  is an open subset of  $\mathbb{R}^n$ , and let  $\vec{a} \in X$ .  $f$  is differentiable at  $a$  iff all of its partial derivatives exist and

$$\lim_{\vec{x} \rightarrow \vec{a}} \frac{f(\vec{x}) - L(\vec{x})}{|\vec{x} - \vec{a}|} = 0$$

where  $L(\vec{x})$  is the linear approximation to  $f$  at  $\vec{a}$ .

**Theorem (Differentiability shortcut).** Let  $f : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$  be a vector-valued function. If all partial derivatives  $\frac{\partial f_i}{\partial x_j}$  exist and are continuous in a neighborhood of  $\vec{a}$  in  $X$ , then  $F$  is differentiable at  $\vec{a}$ .

6.2.8 Directional derivative

Colley [2.6] Trimm [3.7] Brummet [14]

*Definition of Directional derivative.* Let  $f : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$ , where  $X$  is an open subset of  $\mathbb{R}^n$ , and let  $\vec{a} \in X$ . If  $\vec{v}$  is any unit vector in  $X$ , then the directional derivative of  $f$  at  $a$  in the direction of  $v$  is

$$D_{\vec{v}}f(\vec{a}) = \lim_{h \rightarrow 0} \frac{f(\vec{a} + h\vec{v}) - f(\vec{a})}{h}$$

**Theorem.** If  $f$  is differentiable at  $a$ , then

$$D_{\vec{v}}f(\vec{a}) = \nabla f(\vec{a}) \cdot \vec{v}$$

**Theorem.** The gradient is the path of steepest ascent, i.e.

$$D_{\widehat{\nabla f(\vec{a})}}f(\vec{a}) = \max\{D_{\vec{v}}f(\vec{a}) : \vec{v} \in \mathbb{R}^n\}$$

where  $f : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$ .

**Theorem.** Let  $f : X \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}$ , and let  $(a, b, c) \in \mathbb{R}^3$ . Then  $\nabla f(a, b)$  is orthogonal to the level curve at height  $c$ .

6.3 Extrema

6.3.1 Absolute extrema

Colley [4.1] Brummet [15, MVCWUP:69-74(Mar 4-6)]

**Theorem (Quasi-First Derivative Test).** If  $f : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$  has a local maximum or minimum at  $\vec{a}$  and the first order partial derivatives exist, then  $\nabla f \cdot \vec{a} = 0$ , or equivalently all the partials are equal to 0.

**Extreme Value Theorem.** Let  $X$  be a closed and bounded subset of  $\mathbb{R}^n$  and suppose  $f : X \rightarrow \mathbb{R}^n$  is continuous. Then  $f$  attains an absolute maximum and an absolute minimum somewhere on  $X$ .

*Definition of Critical point of f.* A point  $\vec{c}$  in the domain of  $f$  where all of the partial derivatives of  $f$  at  $\vec{c}$  equal 0.

*Definition of Saddle point.* A critical point that is not a max or min.

**Theorem (Method to find absolute minima and maxima).** Let  $C$  be the set of all critical points of  $f$ . Then, the absolute maximum is  $\max\{f(\vec{c}) : \vec{c} \in C\}$  and the absolute minimum is  $\min\{f(\vec{c}) : \vec{c} \in C\}$ .

**Theorem (Method to find absolute minima and maxima with a constraint).** Let  $C$  be the set of all critical points of  $f$ . Let  $S$  be the union of  $C$  and the boundary of the constraint (the constraint constrains the domain on which we are finding absolute minima and maxima). Then, the absolute maximum is  $\max\{f(\vec{c}) : \vec{c} \in C\}$  and the absolute minimum is  $\min\{f(\vec{c}) : \vec{c} \in C\}$ .

6.3.2 Some linalg stuff

*Definition of Matrix multiplication.* The matrix multiplication of the  $m \times n$  matrix  $A$  and the  $n \times p$  matrix  $B$  is made by dot-producting the rows of the first by the columns of the second:

$$[AB_{ij}] = [A_{i*} \cdot B_{*j}] = \left[ \sum_{k=1}^n A_{ik}B_{kj} \right]$$

*Definition of Positive definite.* Let  $A$  be a matrix. Then  $A$  is positive definite iff for all  $v \in \mathbb{R}^n \setminus \{0\}$ ,  $v^T Av > 0$ .

*Definition of Negative definite.* Let  $A$  be a matrix. Then  $A$  is negative definite iff for all  $v \in \mathbb{R}^n \setminus \{0\}$ ,  $v^T Av < 0$ .

**positive semidefinite** and **negative semidefinite** are the same except that the determinant/eigenvalue/pivot/ $v^T Av$  could also be 0.

*Definition of Principal minor.* The determinant of a submatrix of a matrix.

**Definition of Leading principal minor.** The  $k$ th-order leading principal minor is the determinant of the top left submatrix of a matrix, where the 1st-order leading principal minor is the determinant of the 1x1 matrix at its top left corner, the 2nd-order is the determinant of the 2x2 matrix at its top left corner, etc.

**Theorem (Equivalent conditions for positive definiteness).** Let  $A$  be a matrix. Then  $A$  is positive definite iff

- All leading principal minors of  $A$  are positive
- All eigenvalues of  $A$  are positive
- All pivots of  $A$  are positive

**Theorem (Equivalent conditions for negative definiteness).** Let  $A$  be a matrix. Then  $A$  is negative definite iff

- The  $k$ th-order leading principal minor is negative if  $k$  is odd and positive if  $k$  is even
- All eigenvalues of  $A$  are negative
- All pivots of  $A$  are negative
- $-A$  is positive definite

6.3.3 Local extrema, Second Derivative Test and Taylor series

Colley [4.1] Brummet [16, 17, MVCWUP:75-80(Mar 13-14)]

**Definition of Hessian matrix.** The Hessian matrix  $Hf$  of a function  $f : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$  is the matrix of second-order partials

$$[Hf_{ij}] = \left[ \frac{\partial^2 f}{\partial x_i \partial x_j} \right]$$

If  $X \subseteq \mathbb{R}^2$ , then

$$Hf = \begin{bmatrix} f_{xx} & f_{xy} \\ f_{yx} & f_{yy} \end{bmatrix}$$

The **first-order Taylor polynomial** is just the linear approximation

$$T_1(\vec{x}) = f(\vec{a}) + \nabla f(\vec{a}) \cdot (\vec{x} - \vec{a})$$

**Definition of Second-order Taylor polynomial.** The second degree Taylor polynomial for a function  $f \in \mathbb{R}^n \rightarrow \mathbb{R}$  at point  $\vec{a}$  evaluated at point  $\vec{x}$ , where  $\vec{h} := \vec{x} - \vec{a}$ , is:

$$\begin{aligned} T_2(\vec{x}) &= f(\vec{a}) + \sum_{i=1}^n f_{x_i}(\vec{a})h_i + \frac{1}{2} \sum_{i,j=1}^n f_{x_i x_j}(\vec{a})h_i h_j \\ &= f(\vec{a}) + \nabla f(\vec{a}) \cdot \vec{h} + \frac{1}{2} \vec{h}^T Hf(\vec{a}) \vec{h} \end{aligned}$$

Higher-order Taylor polynomials are not very useful.

**Theorem (Second Derivative Test).** Let  $X$  be an open subset of  $\mathbb{R}^n$  and  $f : X \rightarrow \mathbb{R}$  whose 2nd-order and lower partials exist and are continuous on  $X$  ( $f$  is of class  $C^2$ ). Let  $\vec{a} \in X$  be a critical point of  $f$ . Then

- If the Hessian  $Hf(\vec{a})$  is positive definite, then  $f$  has a local minimum at  $\vec{a}$ .
- If the Hessian  $Hf(\vec{a})$  is negative definite, then  $f$  has a local maximum at  $\vec{a}$ .
- If  $\det Hf(\vec{a}) \neq 0$  but  $Hf(\vec{a})$  is neither positive nor negative definite, then  $f$  has a saddle point at  $\vec{a}$ .

Equivalently if  $X \subseteq \mathbb{R}^2$ , let

$$D := f_{xx}(\vec{a})f_{yy}(\vec{a}) - (f_{xy}(\vec{a}))^2 = \det Hf(\vec{a})$$

Then

- If  $D > 0$  and  $f_{xx}(\vec{a}) > 0$ , then  $f$  has a local minimum at  $\vec{a}$ .
- If  $D > 0$  and  $f_{xx}(\vec{a}) < 0$ , then  $f$  has a local maximum at  $\vec{a}$ .
- If  $D < 0$ , then  $f$  has a saddle point at  $\vec{a}$ .
- If  $D = 0$  the test is inconclusive.

(Note that if  $f_{xx}(\vec{a}) = 0$  then  $D \leq 0$ .)

6.3.4 Lagrange multiplier

**Theorem.** If  $f(\vec{x}_0) = c$  is an extreme value (absolute max or min) of  $f$  on  $g$  (the constraint is  $\{\vec{x} : g(\vec{x}) = k\}$ ) and  $\nabla g(\vec{x}_0) \neq 0$ , then at  $\vec{x}_0$ , the level set  $\{\vec{x} : f(\vec{x}) = c\}$  is tangent to  $g(\vec{x}) = k$ .

Equivalently, if  $f(\vec{x}_0) = c$  is an extreme value (absolute max or min) of  $f$  on  $g$  and  $\nabla g(\vec{x}_0) \neq 0$ , then  $\nabla f(\vec{x}_0) = \lambda \nabla g(\vec{x}_0)$ , where  $\lambda \in \mathbb{R}$  is called the **Lagrange multiplier**.

6.4 Integration

6.4.1 Double integrals

Colley [5.1, 5.2] Paul's Notes [15.1, 15.2, 15.3]

Brummet [08, MVCWUP:Feb3(29-33)]

**Definition of Double integral.** The double integral of  $f : X \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}$  over the rectangle  $R$  is

$$\iint_R f(x, y) \, dA = \lim_{n, m \rightarrow \infty} \sum_{i=1}^n \sum_{j=1}^m f(x_i^*, y_j^*) \, \Delta A$$

Generally, the double integral of  $f$  over the region  $R$  is

$$\iint_R f(x, y) \, dA = \lim_{n \rightarrow \infty} \sum_{(x_i^*, y_j^*) \in R} f(x_i^*, y_j^*) \, \Delta A$$

(choose  $n$  points  $(x_i^*, y_j^*)$  in  $R$ , then sum each  $f(x_i^*, y_j^*) \, \Delta A$ )

**Theorem (Fubini's Theorem).** If  $f : X \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}$  is continuous on  $[a, b] \times [c, d]$ , then

$$\iint_R f(x, y) \, dA = \int_a^b \int_c^d f(x, y) \, dy \, dx = \int_c^d \int_a^b f(x, y) \, dx \, dy$$

**Theorem.** If  $f(x, y) = g(x)h(y)$  and  $R = [a, b] \times [c, d]$ , then

$$\iint_R f(x, y) \, dA = \iint_R g(x)h(y) \, dA = \left( \int_a^b g(x) \, dx \right) \left( \int_c^d h(y) \, dy \right)$$

**Theorem (Type I integrals).** If  $f : X \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}$  is defined on  $D = \{(x, y) : a \leq x \leq b, g_1(x) \leq y \leq g_2(x)\}$ , then

$$\iint_D f(x, y) \, dA = \int_a^b \int_{g_1(x)}^{g_2(x)} f(x, y) \, dy \, dx$$

**Theorem (Type II integrals).** If  $f : X \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}$  is defined on  $D = \{(x, y) : h_1(y) \leq x \leq h_2(y), c \leq y \leq d\}$ , then

$$\iint_D f(x, y) \, dA = \int_c^d \int_{h_1(y)}^{h_2(y)} f(x, y) \, dx \, dy$$

**Theorem (Reversing the order of integration).** Sketch the bounds of the region of integration, then just redo the bounds from scratch.

**Theorem (Converting double integrals to polar).**

$$\int_a^b \int_c^d f \, dx \, dy = \int_\alpha^\beta \int_\gamma^\delta f \, r \, dr \, d\theta$$

$a, b, c, d, \alpha, \beta, \gamma, \delta$  may be constants or may depend on the variables. To find the new bounds sketch the bounds and redo the bounds.

**Definition of Triple integral.** The triple integral of  $f$  over the region  $R$  is

$$\iiint_R f \, dA = \lim_{n \rightarrow \infty} \sum_{(x_i^*, y_j^*, z_k^*) \in R} f(x_i^*, y_j^*, z_k^*) \, \Delta A$$

(choose  $n$  points  $(x_i^*, y_j^*, z_k^*)$  in  $R$ , then sum each  $f(x_i^*, y_j^*, z_k^*) \, \Delta A$ )

## 6.4.2 General change of variables

**Theorem (General change of variables).** Given a function  $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$  which takes in an argument in the coordinate system  $X$ , and  $T_{XU} : \mathbb{R}^n \rightarrow \mathbb{R}^n$  is a transformation from coordinates in  $X$  to coordinates in  $U$ ,

$$\int \cdots \int_R f(\vec{x}) dx_1 \cdots dx_n = \int \cdots \int_R f(T_{XU}(\vec{u})) |\det DT_{XU}^{-1}| du_1 \cdots du_n$$

where  $|\det DT_{XU}^{-1}|$  is the absolute determinant of the Jacobian of  $T_{XU}^{-1}$  (the transformation from coordinates in  $U$  to coordinates in  $X$ ), which is also denoted by

$$\left| \frac{\partial(x_1, \dots, x_n)}{\partial(u_1, \dots, u_n)} \right|$$

It can also be computed more easily by taking the inverse of  $DT_{XU}$ :

$$|\det DT_{XU}^{-1}| = \left| \frac{1}{\det DT_{XU}} \right|$$

**Example (Cartesian to spherical).** Converting from Cartesian coordinates to spherical coordinates in  $\mathbb{R}^3$ :

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = T_{XP}^{-1} \left( \begin{bmatrix} \rho \\ \phi \\ \theta \end{bmatrix} \right) = \begin{bmatrix} \rho \sin \phi \cos \theta \\ \rho \sin \phi \sin \theta \\ \rho \cos \phi \end{bmatrix}$$

so then the absolute Jacobian determinant is

$$|\det T_{XP}^{-1}| = \rho^2 \sin \phi$$

## 6.5 Vector fields

### 6.5.1 Vector fields

**Definition of Vector field.** A vector field in  $\mathbb{R}^n$  is a mapping  $F : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^n$ .

**Definition of Flow line.** A flow line of a vector field  $F : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^n$  is a differentiable path  $\vec{x} : I \rightarrow \mathbb{R}^n$  (where  $I$  is an interval on  $\mathbb{R}$ ) such that

$$\vec{x}'(t) = F(\vec{x}(t))$$

That is, the velocity vector of  $\vec{x}$  at time  $t$  is given by the value of the vector field  $F$  at the point on  $x$  at time  $t$ .

**Procedure (Approximating flow line).** Begin at a vector along the flow line. Then the next vector on the vector field in the direction pointed to by this vector is approximately along the flow line. So you can draw a curve through the vectors following the arrows.

### 6.5.2 Conservative vector field

**Definition of Conservative vector field.** A vector field  $\vec{F}$  is conservative iff there exists  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  such that  $\vec{F} = \nabla f$  at all points in  $\mathbb{R}^n$ . Then  $f$  is called the **potential function** for  $F$ .

**Note:** Sometimes in physics, the potential function is defined such that  $\vec{F} = -\nabla f$  - for example,  $\vec{E} = \nabla V$  in E+M.

**Lemma.** A conservative vector field is irrotational.

If a vector field is irrotational and is defined on a domain with no holes, then it is conservative.

### 6.5.3 Divergence and curl

**Definition of Del operator.** In  $\mathbb{R}^3$ , del is defined by

$$\nabla := \begin{bmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} \end{bmatrix}$$

In  $\mathbb{R}^n$ , del is defined by

$$\nabla = \begin{bmatrix} \frac{\partial}{\partial x_1} \\ \vdots \\ \frac{\partial}{\partial x_n} \end{bmatrix}$$

Del is an operator; it takes in a function and outputs a function.

**Definition of Divergence.** Let  $\vec{F} : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^n$  be a differentiable vector field. Then the divergence of  $\vec{F}$  is the scalar field

$$\operatorname{div} \vec{F} = \nabla \cdot \vec{F} = \frac{\partial F_1}{\partial x_1} + \cdots + \frac{\partial F_n}{\partial x_n}$$

**Lemma.** If  $\vec{F}$  represents the flow rate of a fluid, then  $\operatorname{div} \vec{F}$  represents the net mass flow through each point in the domain of  $\vec{F}$ :

- If  $\operatorname{div} \vec{F} > 0$ , then more fluid is flowing out than in.
- If  $\operatorname{div} \vec{F} < 0$ , then more fluid is flowing in than out.
- If  $\operatorname{div} \vec{F} = 0$ , then the same amount of fluid flows in as flows out. In this case,  $\vec{F}$  is considered **incompressible** and **solenoidal**.

The divergence of a vector field represents how "outgoing" the field is at each point, and how source-like (if positive) or sink-like (if negative) each point is.

**Definition of Curl ( $\mathbb{R}^3$ ).** Let  $\vec{F} : X \subseteq \mathbb{R}^3 \rightarrow \mathbb{R}^3$  be a differentiable vector field on  $\mathbb{R}^3$ . Then the curl of  $\vec{F}$  is the vector field

$$\operatorname{curl} \vec{F} = \nabla \times \vec{F}$$

**Definition of Curl ( $\mathbb{R}^2$ ).** Let  $\vec{F} : X \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}^2$  be a differentiable vector field on  $\mathbb{R}^2$ . Then the curl of  $\vec{F}$  is the scalar field

$$\operatorname{curl} \vec{F} = \frac{\partial F_2}{\partial x} - \frac{\partial F_1}{\partial y}$$

This is equivalent to the magnitude of  $\nabla \times \vec{F}$ , where counterclockwise is positive and clockwise is negative (by right-hand rule).

**Definition of Irrotational.** If  $\nabla \times \vec{F} = 0$  everywhere on the vector field  $\vec{F} : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^n$ , then  $\vec{F}$  is considered **irrotational**.

**Lemma.** Let there exist an infinitesimally small sphere at the point  $\vec{x} \in X$ . Let  $\vec{F} : X \subseteq \mathbb{R}^3 \rightarrow \mathbb{R}^3$  be a vector field that represents the velocity of a fluid at each point in  $X$ . Then  $\operatorname{curl} \vec{F}$  is the unique vector such that

- The direction of  $\operatorname{curl} \vec{F}$  is along the axis of rotation of the sphere, following the right-hand rule.
- The magnitude of  $\operatorname{curl} \vec{F}$  is the speed of the rotation of the sphere.

### 6.5.4 Line integrals

**Definition of Scalar line integral.** If  $C$  is a smooth plane curve defined by  $x = x(t)$ ,  $y = y(t)$ ,  $a \leq t \leq b$ , then

$$\int_C f(x, y) ds := \int_a^b f(x(t), y(t)) \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt$$

This generalizes to higher dimensions - if  $C$  is a smooth curve defined by  $\vec{x} = \vec{x}(t)$ ,  $a \leq t \leq b$ , where  $x \in \mathbb{R}^n$ , then

$$\int_C f(\vec{x}) ds = \int_a^b f(\vec{x}(t)) \sqrt{\left(\frac{dx_1}{dt}\right)^2 + \cdots + \left(\frac{dx_n}{dt}\right)^2} dt$$

**Definition of Line integral of a vector field along a smooth curve.** If  $F$  is any continuous vector field defined on a smooth curve  $C$  defined by  $\vec{r}(t)$ ,  $a \leq t \leq b$ , then

$$\int_C \vec{F} \cdot d\vec{r} = \int_C \vec{F} \cdot \hat{T} ds = \int_a^b \vec{F}(\vec{r}(t)) \cdot \vec{r}'(t) dt$$

It represents the work done by moving a particle along the curve  $C$ , if  $F$  is a force field.

**Definition of Orientation-preserving reparamaterization.** Let  $\vec{x} : [a, b] \rightarrow \mathbb{R}^n$  be a piecewise  $C^1$  path, and let  $\vec{F} : X \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^n$  whose domain  $X$  contains the image of  $\vec{x}$ .

If  $\vec{y} : [c, d] \rightarrow \mathbb{R}^n$  is any reparametrization of  $\vec{x}$ , then

- If  $\vec{y}$  is **orientation-preserving**, then  $\int_y \vec{F} d\vec{s} = \int_x \vec{F} d\vec{s}$ .

- 
- If  $\vec{y}$  is **orientation-reversing**, then  $\int_y \vec{F} d\vec{s} = 0 \int_x \vec{F} d\vec{s}$ .

**Definition of Path independence.** A vector field  $\vec{F}$  is path-independent iff for any two paths  $C_1$  and  $C_2$  which have the same start and end points,

$$\int_{C_1} \vec{F} \cdot d\vec{r} = \int_{C_2} \vec{F} \cdot d\vec{r}$$

**Fundamental Theorem of Line Integrals.** Let  $C$  be a smooth curve given by the function  $\vec{r}(t)$  defined on the interval  $t \in [a, b]$ . Let  $f$  be a differentiable function whose gradient  $\nabla f$  is continuous on  $C$ . Then

$$\int_C \nabla f \cdot d\vec{r} = f(\vec{r}(b)) - f(\vec{r}(a))$$

In other words, the line integral of a conservative field along a curve is equal to the potential difference between its endpoints.

This implies that the following statement are equivalent (each implies the others):

- The vector field  $\vec{F}$  is conservative
- The vector field  $\vec{F}$  is path-independent
- $\oint_C \vec{F} \cdot d\vec{r} = 0$  for every closed path  $C$ .

### 6.5.5 Green's Theorem

**Green's Theorem.** Let  $\partial D$  be a positively oriented, piecewise smooth, simple closed curve in the  $xy$ -plane, and  $D$  be the region bounded by  $\partial D$ . If  $P$  and  $Q$  have continuous partial derivatives on an open region containing  $D$ , then

$$\oint_{\partial D} P dx + Q dy = \iint_D \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) dA$$

Equivalently, if  $\vec{F} = x, y \mapsto \begin{bmatrix} P(x, y) \\ Q(x, y) \end{bmatrix}$ , then

$$\oint_{\partial D} \vec{F} \cdot d\vec{r} = \iint_D \text{curl } \vec{F} dA$$

In other words, the circulation of a vector field along a curve is the same as the sum of the curls within the region bounded by the curve.

**Definition of Circulation.** The circulation of the vector field  $\vec{F}$  around the curve  $C$  is

$$\oint_C \vec{F} \cdot d\vec{r}$$

It measures how much  $F$  aligns with the curve  $C$ .

## 6.6 Surfaces

### 6.6.1 Parametric surfaces

**Definition of Parametric/parameterized surface.** Let  $\vec{X} : D \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}^3$  be a one-to-one function (except possibly at the boundary of  $D$ ). Then the image of  $X$  is called a parameterized surface.

**Definition of Normal vector to a parameterized surface.**

Let  $\vec{X} = \begin{bmatrix} u \\ v \end{bmatrix} \mapsto \begin{bmatrix} x(u, v) \\ y(u, v) \\ z(u, v) \end{bmatrix}$  be a parameterization of a surface,

and let  $\vec{u}$  be a vector in the domain of  $\vec{X}$ . Then the tangent vector along the  $u$ -axis is  $\vec{X}_u(\vec{u})$ , where

$$\vec{X}_u = \begin{bmatrix} \frac{\partial x}{\partial u} \\ \frac{\partial y}{\partial u} \\ \frac{\partial z}{\partial u} \end{bmatrix}$$

and similarly the tangent vector along the  $v$ -axis is  $\vec{X}_v(\vec{u})$ .

Then the normal vector to the parameterized surface at the point  $\vec{u}$  is

$$\vec{N} = \vec{X}_u(\vec{u}) \times \vec{X}_v(\vec{u})$$

**Definition of Smooth.** A parameterization  $\vec{X}$  of a surface is smooth at a point if its normal vector is not equal to 0 at that point.

A surface is smooth at a point if there exists a parameterization for that surface which is smooth at that point.

Note that a smooth surface can have non-smooth parameterizations.

### 6.6.2 Surface integrals

**Definition of Scalar surface integral.** The surface integral of  $f$  over the surface  $S$  which is parameterized by  $\vec{X} : D \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}^3 = (u, v) \rightarrow (x, y, z)$  and where  $D$  is the domain of  $\vec{X}$  is

$$\iint_S f dS = \iint_D f(\vec{X}(u, v)) |\vec{X}_u \times \vec{X}_v| dA$$

( $dS$  is a part of the surface area,  $dA$  is a part of the domain)

**Definition of Scalar surface integral in  $\mathbb{R}^3$  for function of two variables.** (This is optional; the definition above can be used to derive this.)

The surface integral of  $f$  over the surface  $S$  defined by  $z = g(x, y)$ , whose domain is  $D$ , is

$$\iint_S f dS = \iint_D f(x, y, g(x, y)) \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2 + 1} dA$$

**Definition of Orientable surface.** A smooth, connected surface  $S$  is orientable iff it is possible to define a single normal vector at each point of  $S$  such that the collection of these normal vectors varies continuously over  $S$ .

**Definition of Closed surface.** A surface is closed iff it is the boundary of some solid region  $E$ .

**Definition of Oriented surface.** A smooth, orientable surface together with a choice of its orientation.

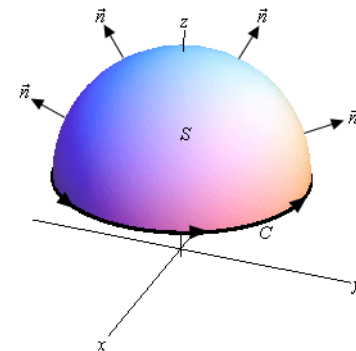
If the surface is closed and encloses the region  $E$ , then it has a **positive orientation** when we choose the set of its normal vectors to point away from  $E$  and a **negative orientation** when we choose the set of its normal vectors to point towards  $E$ .

**Definition of Vector surface integral, flux.** The surface integral or flux of the vector field  $\vec{F}$  over the surface  $S$  which is parameterized by  $\vec{X} : D \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}^3 = (u, v) \rightarrow (x, y, z)$  and where  $D$  is the domain of  $\vec{X}$  is

$$\iint_S \vec{F} \cdot d\vec{S} = \iint_D F(\vec{X}(u, v)) \cdot (\vec{X}_u \times \vec{X}_v) du dv$$

### 6.6.3 Stokes' Theorem

**Definition of Positive oriented boundary.** Given a surface  $S$  whose boundary is the curve  $C$ , the positive orientation of the curve is such that if one were to walk along the curve in that direction, with the vector upwards from the top of their head parallel to the normal vectors of  $S$ , the surface would be to that person's left. Equivalently, you could choose a normal vector and use the right-hand rule (thumb is the normal vector and the positive orientation is given by the curl of the fingers).





**Stoke's Theorem.** Let  $S$  be an oriented smooth surface, bounded by a curve  $\partial S$ , composed of finitely many simple closed smooth differentiable ( $C^1$ ) curves with positive orientation. Let  $\vec{F}$  be a differentiable ( $C^1$ ) vector field whose domain includes  $S$ . Then

$$\oint_{\partial S} \vec{F} \cdot d\vec{r} = \iint_S \nabla \times \vec{F} \cdot d\vec{S}$$

In other words, the circulation of a vector field along a curve is the same as the sum of the curls within the surface bounded by the curve.

#### 6.6.4 Gauss's Theorem

**Gauss's Theorem / Divergence theorem.** Let  $D$  be a solid region in  $\mathbb{R}^3$ , bounded by a surface  $\partial D$ , composed of finitely many smooth closed surfaces with positive orientation. Let  $\vec{F}$  be a differentiable ( $C^1$ ) vector field whose domain includes  $D$ . Then

$$\oiint_{\partial D} \vec{F} \cdot d\vec{S} = \iiint_D \nabla \cdot \vec{F} dV$$

In other words, the flux of a vector field through a closed surface is the same as the sum of the divergences of the vector field through the region bounded by the surface.

This follows from that

- The ratio of flux to volume approaches the divergence as the volume becomes smaller.
- If the region is partitioned into smaller regions, the flux of the region is equal to the sum of the flux of the smaller regions (since the flux of the boundary of the two regions cancels out).

# Linear Algebra (7)

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

## 7.1 Linear equations

**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.

### 7.1.1 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  $\text{RREF}(A)$ .

**Definition of Leading variable, determined variable, basic variable.** A variable in a pivot column.

**Definition of Free variable.** A variable not in a pivot column.

### 7.1.2 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  $u_1, u_2, \dots$ .

### 7.1.3 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).

7.2 Fields

7.2.1 Real and complex numbers

Definition of Field properties. The following properties:

Theorem (Properties of addition). For all  $x, y, z \in F$ :

- (A1) Commutativity:  $x + y = y + x$
- (A2) Associativity:  $(x + y) + z = x + (y + z)$
- (A3) Identity:  $\exists 0 \in \mathbb{R}$  s.t.  $0 + x = x$
- (A4) Additive inverse: For  $x \in F$ ,  $\exists -x \in F$  s.t.  $x + (-x) = 0$

Theorem (Properties of multiplication). For all  $x, y, z \in F$ :

- (M1) Commutativity:  $xy = yx$
- (M2) Associativity:  $(xy)z = x(yz)$
- (M3) Identity:  $\exists 1 \in \mathbb{R}$  s.t.  $1x = x$  and  $1 \neq 0$
- (M4) Additive inverse: For  $x \in F \setminus \{0\}$ ,  $\exists x^{-1} \in F$  s.t.  $xx^{-1} = 1$

Theorem (Distributive property).

- (D)  $x(y + z) = xy + xz$  for all  $x, y, z \in F$ .

7.2.2 Fields

Definition of Field. A set  $F$  which defines the following two operations:

- Addition: an operation that maps  $x, y \in F \rightarrow c \in F$  and satisfies the properties of addition
- Multiplication: an operation that maps  $x, y \in F \rightarrow c \in F$  and satisfies the properties of multiplication

for which the distributive property also holds.

Theorem.  $\mathbb{R}$  and  $\mathbb{C}$  are fields.

Definition of Complex number. A number which can be defined by a pair of real numbers  $a, b$  where the value of the number is equal to  $a + bi$ .

Theorem (Useful things about complex numbers). Let  $z = a + bi$  and  $w = c + di$  be complex numbers. Then:

- $z + w = (a + c) + (b + d)i$
- $zw = (ac - bd) + (bc + ad)i$

Definition of  $F^n$ . For a field  $F$ ,  $F^n$  is the set of all ordered  $n$ -tuples of elements of  $F$ :

$$F^n := \{(x_1, \dots, x_n) : x_1, \dots, x_n \in F\}$$

Definition of Addition in  $F^n$ . If  $a, b \in F^n$ :

$$a + b = (a_1 + b_1, \dots, a_n + b_n)$$

Addition follows the properties of additon (A1-A4).

Definition of Product of element of  $F$  and element of  $F^n$ . If  $\alpha \in F$  and  $x \in F^n$ , then

$$\alpha x = (\alpha x_1, \dots, \alpha x_n)$$

7.3 Vector spaces

2.3 Vector spaces

Definition of Vector space. A vector space over  $F$  is a set  $V$  with the following operations:

- **Vector addition:**  $u \in V, v \in V \mapsto (u + v) \in V$ , which satisfies the properties of addition
- **Scalar multiplication:**  $\alpha \in F, v \in V \mapsto \alpha v \in V$ , which satisfies the properties of scalar multiplication

Definition of Properties of addition. For all  $u, v, w \in V$ :

- (A1) Commutativity:  $u + v = v + u$
- (A2) Associativity:  $(u + v) + w = u + (v + w)$
- (A3) Identity:  $\exists 0 \in \mathbb{R}$  s.t.  $0 + u = u$
- (A4) Additive inverse: For  $u \in F$ ,  $\exists -u \in F$  s.t.  $u + (-u) = 0$

Definition of Properties of scalar multiplication. For all  $\alpha, \beta \in F, v, w \in V$ :

- (S1) Associativity:  $(\alpha\beta)v = \alpha(\beta v)$
- (S2) Distributivity over scalar addition:  $(\alpha + \beta)v = \alpha v + \beta v$
- (S3) Distributivity over vector additon:  $\alpha(v + w) = \alpha v + \alpha w$
- (S4) Multiplicative identity:  $1v = v$

Theorem.  $F^n$  is a vector space.

Theorem. All inverses and identities are unique in a vector space.

Definition of  $F^\omega$ . The set of all sequences of elements of  $F$ :

$$F^\omega := \{(x_1, x_2, \dots) : x_k \in F \text{ for } k \in \mathbb{N}\}$$

where addition and scalar multiplication are defined similarly to  $F^n$ :

$$\begin{aligned} a + b &:= (a_1 + b_1, \dots, a_n + b_n) \\ \alpha x &:= (\alpha x_1, \dots, \alpha x_n) \end{aligned}$$

Definition of  $F^{m,n}$ . The set of all  $m \times n$  matrices with entries in  $F$ , where addition and scalar multiplication are defined as:

$$\begin{aligned} (A + B)_{ij} &:= A_{ij} + B_{ij} \\ (\alpha A)_{ij} &:= \alpha A_{ij} \end{aligned}$$

Definition of Vector space of functions. Let  $V$  be a vector space,  $S$  be a set, and

$$V^S = \{f : S \rightarrow V\}$$

(the set of all functions that map members of  $S$  to members of  $V$ ). Then  $V^S$  is a vector space, if we define for all  $p, q \in V^S, s \in F$ ,

$$(f + g)(s) = f(s) + g(s) \quad (\alpha f)(s) = \alpha(f(s))$$

Definition of Polynomial. A function  $p : F \rightarrow F$  is a polynomial of degree  $n$  iff there exist  $c_0, \dots, c_n \in F$  such that

$$p(x) = c_0 + c_1x + c_2x^2 + \dots c_nx^n = \sum_{k=0}^n c_kx^k$$

$\mathcal{P}(F)$  is the set of all polynomials of any degree with coefficients in  $F$ .  $\mathcal{P}_n(F)$  is the set of all polynomials of degree  $n$  with coefficients in  $F$ .

$\mathcal{P}(F)$  and  $\mathcal{P}_n(F)$  are vector spaces if we define for all  $p, q \in \mathcal{P}_n(F), s \in F$ ,

$$(p + q)(s) = p(s) + q(s) \quad (\alpha p)(s) = \alpha(p(s))$$

7.3.1 Subspaces

Definition of Subspace. Let  $V$  be any vector space, and let  $W$  be a subset of  $V$ . Define vector addition and scalar multiplication on  $W$  by restricting the corresponding operations of  $V$  to  $W$ . If  $W$  is a vector space with respect to the restricted operations of  $V$ , then  $W$  is said to be a subspace of  $V$ .

Definition of Closed. An operation is closed under a set if applying the operation to elements of the set always results in an element of the set.

Definition of Subspace. A subspace of a vector space  $V$  is a subset  $W$  of  $V$  which contains the zero vector and is closed under addition and scalar multiplication.

Theorem. A subset  $W$  of a vector space  $V$  is a subspace iff

- (i)  $W$  is nonempty
- (ii)  $\alpha \in F$  and  $w_1, w_2 \in W$  implies  $\alpha w_1 + w_2 \in W$

Typically, we prove (i) by proving that  $0 \in W$ .

7.3.2 Subspaces of  $F^n$

**Theorem (Subspaces of  $\mathbb{R}^n$ ).**  $\mathbb{R}^n$  contains the following subspaces:

- $\{0\}$
- $\mathbb{R}^n$
- Any line through the origin
- Any plane through the origin
- etc

*Definition of Spanning.* For vectors to span a space is for it to be sufficient to be able to reach any point in the space using the vectors.

*Definition of Independence.* If a vector can be made out of other vectors, then the vector is independent

7.3.3 Intersections and unions of subspaces

**Theorem.** The intersection of any collection of subspaces of  $V$  is a subspace of  $V$ .

**Theorem.** The union of two subspaces of  $V$  is a subspace of  $V$  iff one of the subspaces is contained in the other.

*Definition of Sum of subspaces.* If  $U$  and  $W$  are subspaces of a vector space  $V$ , then

$$U + W := \{u + w : u \in U \text{ and } w \in W\}$$

**Theorem.** If  $U$  and  $W$  are subspaces of  $V$ , then  $U + W$  is the smallest subspace of  $V$  containing both  $U$  and  $W$ .

*Definition of Direct sum.* If  $V_1, \dots, V_n$  are subspaces of  $V$  such that each element of  $\bigoplus_{k=1}^n V_k = V_1 + \dots + V_n$  can be written uniquely as  $\sum_{k=1}^n v_k = v_1 + \dots + v_n$  where  $v_k \in V_k$ , then  $\bigoplus_{k=1}^n V_k$  is a **direct sum** and can be written as  $\bigoplus_{k=1}^n V_k = V_1 \oplus \dots \oplus V_n$ .

**Theorem.** Let  $V_1, \dots, V_n$  be subspaces of  $V$ . Then they are direct sums iff the only way to write  $0 = v_1 + \dots + v_n$  is to take  $v_1 = \dots = v_n = 0$ .

**Theorem.** If  $U$  and  $W$  are subspaces of  $V$ , then  $U + W$  is a direct sum iff  $U \cap W = \{0\}$ . This does not generalize to higher numbers of subspaces.

7.3.4 Spanning

*Definition of Linear combination.* A linear combination of a collection  $v_1, \dots, v_n$  of vectors in vector space  $V$  is a vector of the form

$$\alpha_1 v_1 + \dots + \alpha_n v_n$$

where each  $\alpha_k \in F$ .

*Definition of Span.* Given  $W \subseteq V$  where  $V$  is a vector field, the set of all linear combinations of vectors in  $W$  is called the span of  $W$ .

$$\text{span}(W) := \left\{ \sum_{i=1}^n \alpha_i w_i : \alpha_i \in F, w_i \in W \right\}$$

Additionally, we define

$$\text{span}(\emptyset) = \{0\}$$

*Definition of Subspace generated by a set.* Given  $W \subseteq V$  where  $V$  is a vector field, the subpace generated by  $W$  is the smallest subspace of  $V$  containing  $W$ , or equivalently the intersection of all subspaces of  $V$  containing  $W$ .

**Theorem.** The span of  $W$  is the subspace generated by  $W$ , i.e.  $W$  is the smallest subspace of  $V$  containing  $W$ .

*Definition of Spanning, spanning set.* If  $\text{span}(W) = V$ , then  $W$  spans  $V$  and  $W$  is a spanning set for  $V$ .

*Definition of Finite-dimensional vector space.* A vector space is finite-dimensional iff it has a finite spanning set.

Otherwise, it is infinite-dimensional.

7.3.5 Linear independence

*Definition of Linear independence.* Let  $V$  be a vector space. If  $W \subseteq V$  is a finite set, it is linearly independent iff the only way to write 0 as a combination

$$\alpha_1 v_1 + \dots + \alpha_m v_m = 0$$

is by taking  $\alpha_1 = \dots = \alpha_m = 0$ . We also define  $\emptyset$  to be linearly independent.

If  $W \subseteq V$  is an infinite set, it is linearly independent if every finite subset of  $W$  is linearly independent.

**Theorem.** If  $W \subseteq V$  is linearly independent, any subset  $U \subseteq W$  is linearly independent.

If one vector in  $W$  is a linear combination of the other vectors (including if  $0 \in W$ ), then  $W$  is linearly dependent.

7.3.6 Basis

*Definition. Basis* A basis of  $V$  is a subset of  $V$  which is linearly independent and spans  $V$ .

*Definition of Standard basis of  $F^n$ .*

$$\left\{ \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ \vdots \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 1 \end{bmatrix} \right\}$$

*Definition of  $P_m(F)$ .*

*Definition of Standard basis of  $P_m(F)$ .*

7.3.7 Dimension

**Plus/minus lemma.** Let  $S \subseteq V$  (where  $V$  is a vector space).

- If  $S$  is linearly independent, and  $v$  is not in the span of  $S$ , then  $S \cup \{v\}$  is linearly independent.
- If  $v \in \text{span}(S \setminus \{v\})$ , then  $\text{span}(S) = \text{span}(S \setminus \{v\})$ .

**Theorem.** Let  $V$  be a finite-dimensional vector space and  $S \subseteq V$ . Then,

- If  $\text{span}(S) = V$ , then  $S$  contains a subset  $B$  which is a basis of  $V$
- If  $S$  is linearly independent, then  $S$  can be extended to a basis of  $V$

**Theorem.** Let  $V$  be a finite-dimensional vector space spanned by a set of  $m$  vectors. Then any linearly independent set of vectors in  $V$  is finite and contains no more than  $m$  elements.

7.4 Linear maps

7.4.1 Linear map

*Definition of Linear map.* Let  $V$  and  $W$  be vector spaces over  $F$ . A **linear map** (also called **linear function** or **linear transformation**) from  $V$  to  $W$  is a function  $T : V \rightarrow W$  with the two properties

$$\begin{aligned} T(v_1 + v_2) &= Tv_1 + Tv_2 && \text{(additivity)} \\ T(\alpha v) &= \alpha Tv && \text{(homogeneity)} \end{aligned}$$

Equivalently, it is a function with the property that

$$T(\alpha v_1 + v_2) = \alpha Tv_1 + Tv_2$$

Equivalently, it is a function with the property that

$$T(\alpha_1 v_1 + \alpha_2 v_2) = \alpha_1 Tv_1 + \alpha_2 Tv_2$$

**Note:** Not all elementary linear functions  $y = mx + b$  are linear maps! All linear maps in  $F^1$  are of the form  $y = mx$ .

*Definition of Linear operator.* A function  $T : V \rightarrow V$  which is a linear map.

*Definition of  $\mathcal{L}$ .* For any vector spaces  $V$  and  $W$ ,  $\mathcal{L}(V, W)$  is the set of all linear maps from  $V$  to  $W$ .

$$\mathcal{L}(V) := \mathcal{L}(V, V).$$

$\mathcal{L}(V, W)$  is also called  $\text{Hom}(V, W)$ .

**Linear Map Lemma.** Let  $V$  be a finite-dimensional vector space and  $W$  be a vector space. Suppose  $\{v_1, \dots, v_n\}$  is a basis of  $V$  and  $w_1, \dots, w_n \in W$ . Then there exists a unique linear map  $T : V \rightarrow W$  such that

$$Tv_k = w_k$$

for each  $k \in \{1, \dots, n\}$ .

**Note:** This means that there exists a unique linear map that maps a basis to any vectors we wish, and that a linear map is uniquely determined by its output on a basis.

**Lemma.** If  $T : V \rightarrow W$  is a linear map, then  $T(0) = 0$ .

**Theorem ( $\mathcal{L}(V, W)$  is a vector space).** If we define

$$(S + T)(v) := S + T$$

$$(\alpha T)(v) := \alpha T(v)$$

for  $S, T \in \mathcal{L}(V, W)$ ,  $\alpha \in F$ , then  $\mathcal{L}(V, W)$  is a vector space and is a subspace of  $V^W$ .

**Definition of Product of linear maps.** If  $T \in \mathcal{L}(U, V)$  and  $S \in \mathcal{L}(V, W)$ , then we define the product  $ST \in \mathcal{L}(U, W)$  by  $ST := S \circ T$ .

**Theorem ( $\mathcal{L}(V)$  is a unital associative F-algebra).** The product of linear maps on  $V$  has the following properties:

- **Bilinearity:** For all  $S, T_1, T_2 \in \mathcal{L}(V)$ ,  $\alpha \in F$ ,
  - $S(T_1 + T_2) = ST_1 + ST_2$
  - $(S_1 + S_2)T = S_1T + S_2T$
  - $(\alpha S)T = \alpha(ST) = S(\alpha T)$
- **Associativity:**  $(RS)T = R(ST)$  for all  $R, S, T \in \mathcal{L}(V)$
- **Identity (unital):**  $IT = TI = T$  for all  $T \in \mathcal{L}(V)$ , where  $I$  is the identity map  $x \mapsto x$ .

It is an *F-algebra* because it is a vector space over a field equipped with bilinear multiplication.

### 7.4.2 Kernel

**Definition of Kernel.** The **kernel** or **null space** of a linear map  $T : V \rightarrow W$  is the set of vectors in  $V$  which  $T$  maps to the zero vector of  $W$ :

$$\text{null } T = \ker T := \{v \in V : Tv = 0\} \subseteq V$$

**Theorem (Kernel is subspace of domain).** If  $T : V \rightarrow W$ , then  $\ker T$  is a subspace of  $V$ .

**Definition of Injective.** A map of sets  $f : A \rightarrow B$  is **injective** or **one-to-one** iff  $a_1 \neq a_2$  implies  $f(a_1) \neq f(a_2)$ , or equivalently iff  $f(a_1) = f(a_2)$  implies  $a_1 = a_2$ .

**Theorem (Injective linear map has trivial kernel).** A linear map  $T : V \rightarrow W$  is injective iff  $\ker T = \{0\}$ .

### 7.4.3 Image

**Definition of Image.** Let  $T : V \rightarrow W$  be a linear map. The **image** or **range** of  $T$  is the set of all outputs of  $T$ :

$$\text{range } T = \text{im } T := \{Tv : v \in V\} \subseteq W$$

**Theorem (Image is subspace of codomain).** If  $T : V \rightarrow W$ , then  $\text{im } T$  is a subspace of  $W$ .

**Definition of Surjective.** A map of sets  $f : A \rightarrow B$  is **surjective** iff  $\text{im } f = B$ , or equivalently iff for every  $b \in B$  there exists  $a \in A$  s.t.  $f(a) = b$ .

Iff  $f$  is surjective,  $f$  **maps  $A$  onto  $B$** .

### 7.4.4 Fundamental Theorem

**Fundamental Theorem of Linear Maps.** Let  $T : V \rightarrow W$  be a linear map with  $V$  finite-dimensional. Then  $\text{im } T$  is finite-dimensional and

$$\dim V = \dim \ker T + \dim \text{im } T$$

**Theorem (Corollary to Fundamental Thm).** Let  $V$  and  $W$  be finite-dimensional vector spaces, and let  $T : V \rightarrow W$ . Then

- If  $\dim V > \dim W$ , then  $T$  is not injective.
- If  $\dim V < \dim W$ , then  $T$  is not surjective.

### 7.4.5 Systems of linear equations as linear maps

**Definition of Systems of linear equations as linear maps.** For a linear equation mapping vectors in  $F^n$  to  $F^m$

$$Ax = y$$

we can interpret this as a linear map  $T_A : M^{n \times 1}(F) \rightarrow M^{m \times 1}(F)$  where  $T(x) = Ax$ .

**Theorem.**  $\ker T_A$  is the solution set of the homogeneous system  $Ax = 0$ .

**Theorem.** A homogeneous system of linear equations with more variables than equations has nonzero solutions.

A system of linear equations with more equations than variables has no solution for some choice of constant terms.

### 7.4.6 Isomorphisms

**Definition of Bijective.** Injective and surjective.

**Definition of Isomorphism.** Let  $V$  and  $W$  be vector spaces over  $F$ . An **isomorphism from  $V$  to  $W$**  is a bijective linear map  $T : V \rightarrow W$ . Iff there exists an isomorphism from  $V$  to  $W$ ,  $V$  and  $W$  are **isomorphic**, which is denoted by  $V \cong W$ .

**Definition of Identity map.** The identity map  $\text{id}_V : V \rightarrow V$  is defined such that

$$\text{id}_V(v) = v \quad \text{for } v \in V$$

**Theorem (Isomorphism is an equivalence relation).**

- **Reflexive:** For any vector space  $V$ ,  $\text{id}_V : V \rightarrow V$  is an isomorphism, i.e.  $V \cong V$  for every  $V$ .
- **Symmetric:** If  $T : V \rightarrow W$  is an isomorphism, then  $T^{-1} : W \rightarrow V$  is also an isomorphism. Thus,  $V \cong W$  implies  $W \cong V$ .
- **Transitive:** If  $T_1 : U \rightarrow V$  and  $T_2 : V \rightarrow W$  are isomorphisms, then  $T_2 T_1 : U \rightarrow W$  is an isomorphism. Thus,  $U \cong V$  and  $V \cong W$  implies  $U \cong W$ .

Therefore, isomorphism is an equivalence relation on the collection of all vector spaces over  $F$ .

**Definition of Isomorphism class.** The isomorphism class  $[V]$  of a vector space  $V$  is the set of all vector spaces isomorphic to  $V$ .

**Lemma.** Any two isomorphism classes are disjoint or equal.

**Theorem.** Two finite-dimensional vector spaces over  $F$  are isomorphic iff they have the same dimension.

Equivalently, any finite-dimensional vector space  $V$  over  $F$  is isomorphic to  $F^{\dim V}$ .

**Theorem.** If  $V$  and  $W$  are finite-dimensional vector spaces of the same dimension and  $T : V \rightarrow W$  is a linear map, then if  $T$  is injective or surjective, it is an isomorphism.

**Lemma.**  $\mathcal{P}_n(F) \cong F^{n+1}$ .

### 7.4.7 Coordinates

For the following definitions, let  $B := \{v_1, \dots, v_n\}$  be a basis of  $V$ , where  $V$  is an  $n$ -dimensional vector space over  $F$ .

**Definition of Linear combination map (basis isomorphism).** The **linear combination map or basis isomorphism** is the isomorphism  $L_B : F^n \rightarrow V$  defined by

$$L_B(\vec{x}) = x_1 v_1 + \dots + x_n v_n$$

**Definition of Coordinate isomorphism.** The **coordinate isomorphism** is the isomorphism  $L_B^{-1} : V \rightarrow F^n$ .

This means that for any vector space, its vectors can be expressed as vectors in  $F^n$ .

**Definition of Coordinate vector.** Let  $v$  be a vector in  $V$ . Then the coordinate vector  $[v]_B \in F^n$  of  $v$  is defined as

$$[v]_B := L_B^{-1}(v)$$

Equivalently, it is the vector such that

$$L_B([v]_B) = v$$

*Definition of Ordered basis.* An ordered basis of a  $n$ -dimensional vector space  $V$  is an  $n$ -tuple which is an ordering of a basis of  $V$ .

7.4.8 Matrix of a linear map

*Definition of Matrix of a linear map.* Let  $B_V = (v_1, \dots, v_n)$  be a basis of  $V$  and  $B_W = (w_1, \dots, w_m)$  be a basis of  $W$ . Let  $T : V \rightarrow W$  be a linear map.

Then the matrix of  $T$  with respect to  $B_V$  and  $B_W$  is denoted as

$$[T]_{B_W B_V}$$

It is the  $m \times n$  matrix defined such that its  $j$ th column is the coordinate vector of  $Tv_j$  with respect to  $B_W$ :

$$\left([T]_{B_W B_V}\right)_{*j} = [Tv_j]_{B_W}$$

Equivalently, it is the  $m \times n$  matrix that satisfies

$$Tv_j = \sum_{i=1}^m \left([T]_{B_W B_V}\right)_{ij} w_i$$

**Lemma.** Applying a linear map  $T$  to a vector  $v$  is equivalent to multiplying the coordinate vector of  $v$  by the matrix of  $T$ :

$$[Tv] = [T][v]$$

*Definition of Standard matrix.* The matrix of a linear map  $T : F^n \rightarrow F^m$  with respect to the standard bases of  $F^n$  and  $F^m$ .

**Lemma.**

$$\dim \mathcal{L}(V, W) = (\dim V)(\dim W)$$

**Lemma.** Composing two linear maps  $T_1$  and  $T_2$  is equivalent to multiplying the matrices of the two linear maps:

$$T_1 \circ T_2 = [T_1][T_2]$$

*Definition of Matrix multiplication.* The matrix multiplication of the  $m \times n$  matrix  $A$  and the  $n \times p$  matrix  $B$  is made by dot-producting the rows of the first by the columns of the second:

$$[AB]_{ij} = [A_{i*} \cdot B_{*j}] = \left[\sum_{k=1}^n A_{ik} B_{kj}\right]$$

**Theorem (Properties of matrix multiplication).** Let  $A, B, C$  be matrices and  $r$  and  $s$  be scalars in  $F$ . Then

$$\begin{aligned} A(rB + sC) &= r(AB) + s(AC) \\ (B + C)A &= BA + CA \\ A(BC) &= (AB)C \end{aligned}$$

Effectively, matrix multiplication is distributive and associative. It is not always commutative.

7.4.9 Fundamental matrix spaces

Given a matrix  $A \in F^{m,n}$ , define  $T_A := x \mapsto Ax$ . Then  $T_A : F^n \rightarrow F^m$ .

*Definition of Null space, nullity.* The null space of  $A$  is the kernel of  $T_A$ :

$$\text{Nul } A := \ker T_A = \{x \in F^n : Ax = 0\}$$

which is the solution set of the homogeneous linear system  $Ax = 0$ .

$$\text{nullity } A := \dim \text{Nul } A$$

*Definition of Column space, rank.* The column space of  $A$  is the image of  $T_A$ :

$$\begin{aligned} \text{Col } A &:= \text{im } T_a = \{T_A x : x \in F^n\} \\ &= \{Ax : x \in F^n\} \\ &= \left\{\sum_i i = 1^n x_i A_{*i} : x_i \in F\right\} \\ &= \text{span}\{A_{*1}, \dots, A_{*n}\} \end{aligned}$$

which is the span of the column vectors of the matrix  $A$ .

$$\text{rank } A := \dim \text{Col } A$$

**Lemma.**

$$\begin{aligned} \text{rank } A &= \text{the number of pivot columns} \\ \text{nullity } A &= \text{the number of non-pivot columns} \end{aligned}$$

Therefore,

$$n = \text{nullity } A + \text{rank } A$$

**Procedure (Finding bases of Nul  $A$ , Col  $A$ , Row  $A$ ).**

1. The pivot columns of  $A$  are a basis of Col  $A$ .
2. The pivot rows of  $\text{RREF}(A)$  are a basis of Row  $A$ . (row space is preserved under row operations)
3. The vectors spanning  $Ax = 0$  are a basis of Nul  $A$ .

*Definition of Transpose of a matrix.* If  $A$  is an  $m \times n$  matrix, then its transpose  $A^T$  is the  $n \times m$  matrix obtained by interchanging the rows and columns of  $A$ :

$$[A^T]_{ij} = [A]_{ji}$$

*Definition of Row space.* The row space of  $A$  is the span of the row vectors of  $A$ :

$$\text{Row } A := \text{span}\{A_{1*}, \dots, A_{m*}\} = \text{Col } A^T$$

**Lemma.**

$$\dim \text{Row } A = \dim \text{Col } A = \text{rank } A$$

*Definition of Left null space.* The left null space of  $A$  is the null space of  $A^T$ . It is the solution set of the homogeneous linear system  $A^T y = 0$  or equivalently of  $y^T A = 0^T$ .

**Procedure (Finding the left null space without column operations).** To find the left null space of the  $n \times m$  matrix  $A$ , make a column vector  $b = (b_1, \dots, b_m)^T$  and calculate  $\text{RREF}([A|b])$ . Then the basis of the left null space is given by the rows of  $\text{RREF}([A|b])$  for which the left side is all zero (where  $b_1, \dots, b_m$  are the basis in which  $A$  is expressed in (the basis  $B$  for which  $A = [T]_B$ , which is usually the standard basis)).

Alternately, calculate  $\text{RREF}([A|I])$ , then the basis of the left null space is given by the rows of  $\text{RREF}([A|I])$  for which the left side is all zero.

7.4.10 Invertible matrices

*Definition of Invertible matrix.* Let  $A$  be an  $n \times n$  matrix. If there exists an  $n \times n$  matrix  $B$  s.t.  $AB = BA = I$ , then  $A$  is **invertible** and **non-singular** and  $B$  is the **inverse** of  $A$ :

$$A^{-1} := B$$

A matrix which is not invertible is **non-invertible** and **singular**.

**Lemma.** The matrix of an isomorphism of finite-dimensional vector spaces is invertible.

**Lemma.** If a matrix is invertible, it has a unique inverse.

**Lemma.** Any finite product  $A_1 \cdots A_k$  of invertible  $n \times n$  matrices is invertible with

$$(A_1 \cdots A_k)^{-1} = A_k^{-1} \cdots A_1^{-1}$$

*Definition of Elementary matrix.* An  $n \times n$  matrix is an **elementary matrix** if it can be obtained from the  $n \times n$  identity matrix by a single elementary row operation.

**Theorem.** If  $e : F^{n,n} \rightarrow F^{n,n}$  is an elementary row operation and  $A \in F^{n,n}$ , then

$$e(A) = e(I)A$$

**Invertible Matrix Theorem.** If  $A$  is an  $n \times n$  matrix, then the following conditions are equivalent:

- $A$  is invertible.
- $A$  is row-equivalent to the  $n \times n$  identity matrix.
- $A$  is a product of elementary matrices.

**Theorem.** If  $A$  is an invertible  $n \times n$  matrix and  $E_k \cdots E_1 A = I$  where each  $E_j$  is an elementary matrix, then  $E_k \cdots E_1 I = A^{-1}$ .

**Lemma.** If  $A$  is row-equivalent to  $I$ , then  $[A|I]$  is row-equivalent to  $[I|A^{-1}]$ . Otherwise,  $A$  doesn't have an inverse.

**Procedure (Computation of  $A^{-1}$ ).** Row-reduce the augmented matrix  $[A|I]$ . If  $A$  is row-equivalent to  $I$ , then  $\text{RREF}([A|I]) = [I|A^{-1}]$ . Otherwise,  $A$  doesn't have an inverse.

**Lemma.** The linear system  $Ax = y$  of  $n$  equations with  $n$  unknowns has a unique solution iff  $A$  is invertible.

#### 7.4.11 Change of basis

**Definition of Change of basis matrix.** The **change of basis matrix** or **transition matrix** of an  $n$ -dimensional vector space  $V$  with relation to the ordered bases  $B$  and  $B'$  is the  $n \times n$  matrix whose  $j$ th column is the coordinate vector of the  $j$ th vector in  $B$  with respect to  $B'$ :

$$C_{*j} := [v_j]_{B'}$$

**Procedure (Finding the transition matrix).** Given bases  $B$  and  $B'$ , row-reduce the augmented matrix  $[[w_i] | [v_i]]$ , whose first  $n$  columns are the coordinate vectors  $[w_i]$  of the vectors of  $B'$  and whose last  $n$  columns are the coordinate vectors  $[v_i]$  of the vectors of  $B$ . Then the transition matrix from  $B$  to  $B'$  is the right-hand side of  $\text{RREF}([w_i] | [v_i])$ .

**Lemma (Inverting a transition matrix).**

$$C_{B' \rightarrow B} = C_{B \rightarrow B'}^{-1}$$

Note that  $C_{B' \rightarrow B}$  is the matrix formed by the coordinate vectors of the basis vectors of  $B'$  with respect to  $B$ .

**Lemma (Changing the basis of a vector).** If  $B$  and  $B'$  are bases of  $V$ ,  $v \in V$ , and  $C_{B \rightarrow B'}$  is the transition matrix from  $B$  to  $B'$ , then

$$[v]_{B'} = C_{B \rightarrow B'} [v]_B$$

**Lemma (Changing the basis of a linear map by changing its matrix).** If  $B$  and  $B'$  are bases of  $V$ ,  $T \in \mathcal{L}(V)$ , and  $C_{B \rightarrow B'}$  is the transition matrix from  $B$  to  $B'$ , then

$$[T]_{B'} = C_{B \rightarrow B'} [T]_B C_{B' \rightarrow B}$$

**Procedure (Changing the basis of a linear map by applying the linear map to basis vectors).** If  $B$  and  $B' = (w_1, \dots, w_n)$  are bases of  $V$ ,  $T \in \mathcal{L}(V)$ , and  $C_{B \rightarrow B'}$  is the transition matrix from  $B$  to  $B'$ , then

$$T_{B'} = [C_{B \rightarrow B'} [T]_B [w_1]_B \quad \cdots \quad C_{B \rightarrow B'} [T]_B [w_n]_B]$$

(Apply  $T$  to each of the basis vectors of  $B'$  and then convert  $T w_i$  to the basis  $B'$ )

#### 7.4.12 Similarity

**Definition of Similar matrices.** Two  $n \times n$  matrices  $A$  and  $B$  are similar if there exists an invertible matrix  $C$  s.t.  $B = C^{-1}AC$ .

Similarity is an equivalence relation on  $F^{n,n}$ .

**Definition of Similarity invariant.** A property of a  $n \times n$  matrix  $A$  which holds for all matrices similar to  $A$ .

**Theorem (Useful similarity invariants).** The following properties are similarity invariants:

1. invertibility
2. nullity
3. rank

#### 7.4.13 Linear functionals

**Definition of Linear functional.** Let  $V$  be a vector space over  $F$ . Then a linear map  $T : V \rightarrow F$  is a **linear functional** on  $V$ .

**Definition of Dual space.** Let  $V$  be a vector space over  $F$ . Then the dual space of  $V$  is the vector space of linear functionals on  $V$ ,  $V^* := \mathcal{L}(V, F)$ .

**Definition of Kronecker delta.**

$$\delta_{ij} := \begin{cases} 1, & \text{if } i = j \\ 0, & \text{if } i \neq j \end{cases}$$

**Definition of  $i$ th coordinate function.**

**Definition of Dual basis.**

**Lemma.** Let  $V$  be an  $n$ -dimensional vector space and  $B = \{v_1, \dots, v_n\}$  be a basis of  $V$ . Then there for each  $i \in \{1, \dots, n\}$  there exists a unique linear functional  $f_i$  (called the  **$i$ th coordinate function for  $B$** ) such that

$$f_i(v_j) = \delta_{ij} \quad \text{for all } j \in \{1, \dots, n\}$$

For any  $v \in V$ , we can express  $v$  as a linear combination of elements of  $B$ , where the coefficients are given by  $f_i(v)$ :

$$v = \sum_{j=1}^n f_j(v) v_j$$

Additionally,

$$B^* := f_1, \dots, f_n$$

is a basis of  $V^*$ , and is called the **dual basis** of the basis  $B$  of  $V$ .

Any linear functional  $f : V \rightarrow F$  can be written uniquely as

$$f = \sum_{i=1}^n f(v_i) f_i$$

and  $f(v)$  can be written as

$$f(v) = \sum_{i=1}^n f(v_i) ([v]_B)_i$$

#### 7.4.14 Trace

**Definition of Trace of a matrix.** The trace of an  $n \times n$  matrix  $A$  is the sum of the diagonal elements of  $A$ :

$$\text{tr}(A) := \sum_{i=1}^n A_{ii}$$

$\text{tr} : F^{n,n} \rightarrow F$  is a linear functional.

**Theorem (Properties of the trace).** Let  $A, B$  be  $n \times n$  matrices and  $c$  be a scalar. Then

- $\text{tr}(A + B) = \text{tr}(A) + \text{tr}(B)$
- $\text{tr}(cA) = c \text{tr}(A)$
- $\text{tr}(A^T) = \text{tr}(A)$
- $\text{tr}(AB) = \text{tr}(BA)$  (this generalizes to more than 2 factors)
- The trace is similarity-invariant: if  $A$  and  $B$  are similar then  $\text{tr}(A) = \text{tr}(B)$

### 7.4.15 Transpose

**Definition of Transpose of linear map.** Let  $V$  and  $W$  be vector spaces over  $F$ , and let  $T \in \mathcal{L}(V, W)$ . The **transpose** of  $T$  or **dual map** of  $T$  is the linear map  $T^* = T^T \in \mathcal{L}(W^*, V^*)$  defined for each  $f \in W^*$  by

$$T^*(f) = T^T(f) := f \circ T$$

That is, for each linear functional  $f \in W^*$ ,  $T^T(f)$  is the linear functional in  $V^*$  defined by (for each  $v \in V$ )

$$T^T(f)(v) = f(Tv)$$

**Theorem (Properties of the transpose).** For all linear maps  $T_1, T_2, T$  and  $\alpha \in F$ ,

- $(T_1 + T_2)^T = \alpha T_1^T + T_2^T$  (the map  $T \mapsto T^T$  is linear)
- $(T_1 \circ T_2)^T = T_2^T + T_1^T$

**Theorem (Matrix of transpose is transpose of matrix).** The matrix of  $T^T$  is the transpose of the matrix of  $T$ :

$$[T^T]_{B_W^* B_V^*} = ([T]_{B_V B_W})^T$$

**Lemma.** Let  $V$  and  $W$  be finite-dimensional vector spaces,  $T \in \mathcal{L}(V, W)$  and  $g \in W^*$ . Choose ordered bases  $B_V = (v_1, \dots, v_n)$  and  $B_W = (w_1, \dots, w_m)$  for  $V$  and  $W$ , respectively, and let  $B_V^* = (f_1, \dots, f_n)$  and  $B_W^* = (g_1, \dots, g_m)$  be the corresponding dual bases of  $V^*$  and  $W^*$ . Let  $S = (1)$  be the standard ordered basis of  $F$ . Then

$$[T^T g]_{B_V^*, S} = [g]_{B_W^*, S} [T]_{V, W}$$

**Lemma.** Let  $V$  and  $W$  be finite-dimensional vector spaces,  $T \in \mathcal{L}(V, W)$ ,  $T^T \in \mathcal{L}(W^*, V^*)$ . Then:

- $\text{rank } T^T = \text{rank } T \leq \min\{\dim V, \dim W\}$
- $T$  is injective iff  $T^T$  is surjective
- $T$  is surjective iff  $T^T$  is injective

## 7.5 Multilinear algebra and determinants

### 7.5.1 Bilinear forms

**Definition of Bilinear form.** Let  $V$  be a vector space over  $F$ . A **bilinear form** on  $V$  is a function  $B : V \times V \rightarrow F$  which is linear in each variable separately when the other variable is held constant. That is, for all  $v_1, v_2, v \in V$  and  $\alpha B(v, v_1) + B(v, v_2)$ ,

$$B(\alpha v_1 + v_2, v) = \alpha B(v_1, v) + B(v_2, v)$$

and

$$B(v, \alpha v_1 + v_2) = \alpha B(v, v_1) + B(v, v_2)$$

**Lemma.** If  $V$  is a vector space over  $F$  and  $f, g \in \mathcal{L}(V, F)$ , then  $B(u, v) := f(u)g(v)$  is a bilinear form on  $V$ .

**Definition.**  $V^{(2)}$  denotes the set of all bilinear forms on  $V$ .

**Lemma.**  $V^{(2)}$  is a subspace of  $V \times V \rightarrow F$ .

**Definition of Matrix of a bilinear form.** Let  $B$  be a bilinear form on  $V$  and let  $\vec{e} = (e_1, \dots, e_n)$  be an ordered basis of  $V$ . Then the matrix of  $B$  with respect to  $\vec{e}$  is the matrix  $[B]$  defined by:

$$[B]_{ij} = B(e_i, e_j)$$

**Theorem.** If  $B$  is a bilinear form on  $V$ ,  $[B]$  is its matrix with respect to the ordered basis  $\vec{e}$ ,  $v, w \in F$ , and  $[v]$  and  $[w]$  are the coordinate vectors of  $v$  and  $w$  with respect to the ordered basis  $\vec{e}$ , then

$$B(v, w) = [v]^T [B] [w]$$

### 7.5.2 Symmetric bilinear forms

**Definition of Symmetric bilinear form.** A bilinear form  $B \in V^{(2)}$  is symmetric iff  $B(u, w) = B(w, u)$  for all  $u, w \in V$ . The set of all symmetric bilinear forms on  $V$  is denoted by  $V_{\text{sym}}^{(2)}$ .

**Definition of Symmetric matrix.** An  $n \times n$  matrix  $A$  is symmetric iff  $A^T = A$ .

**Theorem.** If  $B \in V^{(2)}$ , then the following conditions are equivalent.

- $B$  is a symmetric bilinear form on  $V$ .
- $[B]$  is a symmetric matrix for every basis of  $V$ .
- $[B]$  is a symmetric matrix for some basis of  $V$ .
- $[B]$  is a diagonal matrix for some basis of  $V$ .

### 7.5.3 Alternating bilinear forms

**Definition of Alternating bilinear form.** A bilinear form  $B \in V^{(2)}$  is alternating if

$$B(u, u) = -B(u, u)$$

for all  $u, w \in V$ . The set of alternating bilinear forms on  $V$  is denoted by  $V_{\text{alt}}^{(2)}$ .

**Definition of Antisymmetric matrix.** A matrix  $A$  is antisymmetric iff  $A^T = -A$ .

**Theorem.** If  $B \in V^{(2)}$ , then the following conditions are equivalent.

- $B$  is an alternating bilinear form on  $V$ .
- $[B]$  is an antisymmetric matrix for every basis of  $V$ .
- $B(v, v) = 0$  for all  $v \in V$

**Lemma.**  $V^{(2)} = V_{\text{sym}}^{(2)} \oplus V_{\text{alt}}^{(2)}$ , and  $V_{\text{sym}}^{(2)}$  and  $V_{\text{alt}}^{(2)}$  are subspaces of  $V^{(2)}$ .

### 7.5.4 Multilinear forms

**Definition.**

$$V^m := \underbrace{V \times V \times \dots \times V}_{m \text{ times}}$$

**Definition of Multilinear form.** An  $m$ -linear form on  $V$  is a map which is linear in each entry when all other entries are held fixed.

The set of  $m$ -linear forms on  $V$  is denoted by  $V^{(m)}$ .

### 7.5.5 Alternating multilinear forms

**Definition of Alternating multilinear form.** An  $m$ -linear form  $M$  is alternating iff

$$M(v_1, \dots, v_i, \dots, v_j, \dots, v_m) = -M(v_1, \dots, v_j, \dots, v_i, \dots, v_m)$$

for all  $i, j$ .

**Lemma.**  $M \in V^{(m)}$  is alternating iff  $v_i = v_j$  implies  $M(v_1, \dots, v_m) = 0$  for all  $i \neq j \in [1, m]$ .

**Lemma.** If  $M \in V_{\text{alt}}^{(m)}$  and  $\{v_1, \dots, v_m\}$  is linearly dependent, then  $M(v_1, \dots, v_m) = 0$ .

**Lemma.** If  $m > \dim V$ , then  $\dim V_{\text{alt}}^{(m)} = 0$ .

### 7.5.6 Permutations

**Definition of Permutation.** A permutation of the set  $A = \{1, 2, \dots, m\}$  is a bijection  $\sigma : A \rightarrow A$  (equivalently, a reordering of the ordered list  $A$ ). It is often denoted by a matrix

$$\begin{bmatrix} 1 & 2 & \dots & m \\ \sigma(1) & \sigma(2) & \dots & \sigma(m) \end{bmatrix}$$

where the inputs form the first row and the corresponding outputs form the second row.

**Definition of Group.** A group is a set  $G$  which contains a binary operation  $\cdot$  such that

- **Identity:** There exists an identity element  $e \in G$  such that  $a \cdot e = a$
- **Inverse:** There exists an inverse  $a^{-1}$  for each  $a \in G$  such that  $a \cdot a^{-1} = I$
- **Associativity:**  $(a \cdot b) \cdot c = a \cdot (b \cdot c)$

**Theorem.** The set  $S_m$  of all permutations of  $A = \{1, 2, \dots, m\}$  is a group under composition. The identity element is the trivial permutation  $x \mapsto x$ :

$$\begin{bmatrix} 1 & 2 & \dots & m \\ 1 & 2 & \dots & m \end{bmatrix}$$



The inverse of a permutation is denoted  $\sigma^{-1}$ , and the composition of two permutations is denoted  $\tau \circ \sigma = \tau\sigma$ .

**Definition of Cyclic permutation,  $r$ -cycle.** A **cyclic permutation** or  **$r$ -cycle** is a permutation defined by and denoted by a list  $(a_1 \ a_2 \ \dots \ a_r)$  where the  $a_i$  are distinct, such that  $\sigma(a_i) = a_{i+1}$  for  $i \in [1, r]$ ,  $\sigma(a_r) = a_1$ , and  $\sigma(a_l) = a_l$  for  $l > r$ .

A 2-cycle is also called a **transposition**.

**Definition of Disjoint cycles.** Cycles which share no elements in common.

**Theorem.** Any permutation  $\sigma$  can be written as a composition of disjoint transpositions.

**Definition of Even, odd, sign.** A permutation  $\sigma$  is **even** and  $\text{sgn}(\sigma) = +1$  iff it is a product of an even number of disjoint transpositions.

It is **odd** and  $\text{sgn}(\sigma) = -1$  iff it is a product of an odd number of disjoint transpositions.

**Procedure (Writing a permutation as a series of disjoint cycles).** Take any element  $a$  of the input set  $A$ , and apply  $\sigma$  repeatedly until  $a = \sigma \dots \sigma(a)$ . Then we have cycle  $a \mapsto \sigma(a) \mapsto \dots \mapsto \sigma \dots \sigma(a) = a$ . Repeat for all remaining elements that are not part of this cycle.

**Procedure (Writing a permutation as a series of disjoint transpositions).** Apply the above procedure to the permutation. Then for each of the disjoint cycles in the series that are not transpositions, apply that procedure to each of those cycles until they are transpositions (2-cycles).

**Lemma.**  $\text{sgn}(\tau\sigma) = \text{sgn}(\tau)\text{sgn}(\sigma)$  for all  $\tau, \sigma \in S_m$ .

**Lemma.** An  $r$ -cycle is an even permutation iff  $r$  is odd, and an odd permutation iff  $r$  is even.

**Procedure (Determining the sign of a permutation).** Decompose the permutation into a product of disjoint cycles. Then the parity (oddness/evenness) of the permutation is the number of cycles of even length in its decomposition.

## 7.5.7 Determinant

**Definition.**  $[v_1 \dots v_n]$  is the matrix whose  $j$ th column is  $v_j$ .

$|v_1 \dots v_n|$  is the determinant of said matrix.

**Definition of Determinant of a linear operator.** For  $T \in \mathcal{L}(V)$ , the **determinant** of  $T$  is the unique scalar such that  $M_T := M \circ T = (\det T)M$  for all  $M \in V_{\text{alt}}^{(\dim V)}$ .

**Definition of Determinant of a square matrix.** Let  $n$  be a positive integer,  $A$  be an  $n \times n$  matrix with entries in  $F$ , and  $T \in \mathcal{L}(F^n)$  be the operator whose matrix with respect to the standard basis of  $F^n$  is  $A$ . Then the determinant of  $A$  is  $\det A := \det T$ .

**Lemma.** Let  $(v_1, \dots, v_n)$  be an ordered  $n$ -tuple of column vectors. Then the map  $(v_1, \dots, v_n) \mapsto |v_1 \dots v_n|$  is an alternating  $n$ -linear form on  $F^n$ .

**Lemma ( $O(n!)$  method for calculating determinant).** If  $A$  is an  $n \times n$  matrix,

$$\det A = \sum_{\sigma \in S_n} \text{sgn}(\sigma) A_{\sigma(1)1} \dots A_{\sigma(n)n}$$

**Theorem (Cofactor method (also  $O(n!)$ )).** Let  $A$  be an  $n \times n$  matrix. Define  $A[i|j]$  to be the result of removing the  $i$ th row and  $j$ th column from  $A$ . Define the  **$ij$ -cofactor** of  $A$  to be

$$C_{ij} := (-1)^{i+j} \det(A[i|j])$$

Then for any row numbered  $i$ ,

$$\det A = \sum_{k=1}^n A_{ik} C_{ik}$$

And for any column numbered  $j$ ,

$$\det A = \sum_{k=1}^n A_{kj} C_{kj}$$

Note that the coefficient  $(-1)^{i+j}$  in  $C_{ij}$  forms the following pattern:

$$\begin{bmatrix} + & - & + & \dots \\ - & + & - & \\ + & - & + & \\ \vdots & & & \ddots \end{bmatrix}$$

**Lemma.** If  $A$  is a triangular matrix with  $\lambda_1, \dots, \lambda_n$  on the diagonal, then  $\det A = \lambda_1 \dots \lambda_n$  ( $\det A$  is the product of the elements on the diagonal).

## 7.5.8 Properties of the determinant

**Theorem (Determinant is multiplicative).**

- If  $S, T \in \mathcal{L}(V)$ , then  $\det(ST) = (\det S)(\det T)$ .
- If  $A$  and  $B$  are  $n \times n$  matrices, then  $\det(AB) = (\det A)(\det B)$ .

**Theorem.** A linear operator  $T \in \mathcal{L}(V)$  is an isomorphism iff  $\det T \neq 0$ .

If  $T$  is an isomorphism, then  $\det(T^{-1}) = (\det T)^{-1}$ .

**Theorem.** The following are equivalent:

- $A$  is invertible.
- $\det A \neq 0$ .
- The homogeneous system  $AX = 0$  has only the unique solution.

**Theorem (Determinant is similarity invariant).** Let  $T \in \mathcal{L}(V)$  and  $S : W \rightarrow V$  be an invertible linear map. Then

$$\det(S^{-1}TS) = \det T$$

**Theorem.** For all  $T \in \mathcal{L}(V)$ ,  $\det T = \det[T]$ , where  $[T]$  is the matrix of  $T$  with respect to any basis of  $V$ .

**Theorem.** If  $A$  is a square matrix, or if  $A \in \mathcal{L}(V)$ , then

$$\det(A^T) = \det(A)$$

**Theorem (Effect of row and column operations on the determinant).** Let  $A$  be an  $n \times n$  matrix.

- If two rows or columns of  $A$  are equal, then  $\det A = 0$ .
- If  $B$  is the result of swapping two rows or columns of  $A$ , then  $\det B = -\det A$ .
- If  $B$  is the result of multiplying one row or column of  $A$  by the scalar  $\lambda$ , then  $\det B = \lambda \det A$ .
- If  $B$  is the result of replacing a column or row by the sum of itself and a scalar multiple of another column or row, then  $\det B = \det A$ . (this does not apply adding a column to a scalar multiple of a row or vice-versa.)

**Theorem (Effect of elementary row operations (summary)).** Let  $A$  be an  $n \times n$  matrix.

- **Scaling:**  $R_i \mapsto cR_i \implies \det B = c \det A$ .
- **Replacement:**  $R_i \mapsto R_i + cR_j \implies \det B = \det A$
- **Interchange:**  $R_i \leftrightarrow R_j \implies \det B = -\det A$

**Procedure ( $O(n^3)$  procedure for finding determinant).** Row-reduce the matrix  $A$  to row-echelon form ( $R := \text{REF}(A)$ ). Then  $\det R$  is the product of the items along the diagonal of  $R$ . To find  $\det A$ , apply the above theorems.

## 7.5.9 Cramer's rule

**Definition of Adjugate matrix.** Let  $A$  be an  $n \times n$  matrix. Then the adjugate matrix of  $A$  is the transpose of the matrix of cofactors, i.e.

$$\text{adj } A = C^T$$

where  $C$  is defined by

$$C_{ij} = (-1)^{i+j} \det(A[i|j])$$

**Lemma.** Let  $A$  be an invertible  $n \times n$  matrix. Then

$$A^{-1} = \frac{1}{\det A} \operatorname{adj} A$$

**Theorem (Cramer’s Rule).** Let  $A$  be an invertible  $n \times n$  matrix. For any  $\vec{b} \in \mathbb{R}^n$ . the unique solution  $\vec{x}$  of the linear system  $A\vec{x} = \vec{b}$  has entries given by

$$x_i = \frac{\det A_i(\vec{b})}{\det A}$$

where  $A_i(\vec{b})$  is the result of replacing the  $i$ th column of  $A$  by  $\vec{b}$ .

## 7.6 Eigenvalues and eigenvectors

### 7.6.1 Eigenvalues and eigenvectors

**Theorem (Diagonality condition).** Let  $V$  be a finite-dimensional vector space,  $B = (v_1, \dots, v_n)$  be an ordered basis for  $V$ , and  $T \in \mathcal{L}(V)$ . Then  $[T]_B$  is diagonal iff  $T(v_i) = \lambda_i v_i$  for all  $i$ , where  $\lambda_i$  is the  $i$ th element along the diagonal of  $[T]_B$ .

**Definition of Eigenvalue, eigenvector of a linear operator.** Let  $V$  be a vector space and  $T \in \mathcal{L}(V)$ . An **eigenvalue** of  $T$  is a scalar  $\lambda$  s.t. there exists a nonzero vector  $v \in V$  s.t.

$$T(v) = \lambda v$$

The vector  $v$  is the **eigenvector** of  $T$  associated with the eigenvalue  $\lambda$ .

**Lemma.** If  $v$  is an eigenvector of  $T$  associated with eigenvalue  $\lambda$  and if  $B$  is a basis of  $V$ , then

$$[T(v)]_B = \lambda[v]_B$$

**Definition of Eigenvalue, eigenvector of a square matrix.** An **eigenvalue** of the  $n \times n$  matrix  $A$  is a scalar  $\lambda$  s.t. there exists a nonzero vector  $v \in \mathbb{R}^n$  s.t.

$$Av = \lambda v$$

The vector  $v$  is the **eigenvector** of  $A$  associated with the eigenvalue  $\lambda$ .

**Lemma.** Similar matrices have the same eigenvalues.

Any matrix representing  $T \in \mathcal{L}(V)$  has the same eigenvalues as  $T$ .

**Definition of Eigenspace.** A scalar  $\lambda$  is an eigenvalue of  $A$  iff  $Av = \lambda v$  has a nontrivial solution. This is equivalent to the homogeneous linear system (where  $I$  is the  $n \times n$  identity matrix)

$$(A - \lambda I)v = 0$$

The set of all solutions to this equation is the **eigenspace** of  $A$  associated to the eigenvalue  $\lambda$ , which we denote by  $E_\lambda$ .

**Lemma.** If  $A \in \mathbb{R}^{n \times n}$ , then the eigenspace of  $A$  corresponding to  $\lambda$  is a subspace of  $\mathbb{R}^n$ .

**Lemma.** Let  $A$  be an  $n \times n$  matrix. Then  $\det(\lambda I - A)$  is a monic (leading coefficient 1) polynomial of degree  $n$  on  $\lambda$ .

**Definition.** For any  $n \times n$  matrix  $A$ , the monic, degree  $n$  polynomial  $\det(\lambda I - A)$  is the **characteristic polynomial** of  $A$ . The equation

$$\det(\lambda I - A) = 0$$

is the **characteristic equation** of  $A$ .

**Lemma.** Similar matrices have the same characteristic equation.

**Lemma.** The eigenvalues of a triangular matrix are the entries on the main diagonal.

**Theorem (Rational root theorem).** Let  $p(x) = a_n x^n + a_{n-1} x^{n-1} + \dots + a_1 x + a_0$  be a degree- $n$  polynomial with integer coefficients. If  $x = \frac{p}{q}$  is a rational root of  $p(x)$ , then  $a_0$  is divisible by  $p$  and  $a_n$  is divisible by  $q$ .

### 7.6.2 Diagonalizable operators

**Definition of Diagonalizable operator.** A linear operator  $T \in \mathcal{L}(V)$  is said to be diagonalizable if there exists a basis consisting of eigenvectors of  $T$ . Such a basis is called an **eigenbasis**.

**Lemma.** If  $T \in \mathcal{L}(V)$ , then every set of eigenvectors corresponding to distinct eigenvalues of  $T$  is linearly independent.

**Lemma.** If  $\dim V = n$  and  $T \in \mathcal{L}(V)$  has  $n$  distinct eigenvalues, then  $T$  is diagonalizable.

**Definition of Multiplicity of a root of a polynomial.** Let  $p(x)$  be a polynomial. Then an element  $a \in F$  is a root of multiplicity  $k$  iff there exists a polynomial  $s(x)$  such that  $s(a) \neq 0$  and  $p(x) = (x - a)^k s(x)$ .

**Definition of Algebraic multiplicity.** The algebraic multiplicity of the eigenvalue  $\lambda_k$  is the multiplicity of  $\lambda_k$  as a root of the characteristic polynomial of  $A$ .

**Definition of Geometric multiplicity.** The geometric multiplicity of the eigenvalue  $\lambda_k$  is the dimension of the eigenspace corresponding to  $\lambda_k$ .

**Theorem (Conditions equivalent to diagonalizability).** Let  $V$  be a finite-dimensional vector space,  $T \in \mathcal{L}(V)$ , and  $\lambda_1, \dots, \lambda_n$  be the distinct eigenvalues of  $T$ . Then the following are equivalent:

- $V$  has a basis consisting of eigenvectors of  $T$
- $V = E_{\lambda_1} \oplus \dots \oplus E_{\lambda_m}$
- $\dim V = \dim E_{\lambda_1} + \dots + \dim E_{\lambda_m}$

- The geometric multiplicity of each eigenvector is equal to its algebraic multiplicity.

**Procedure (Diagonalizing a linear operator).** Let  $T \in \mathcal{L}(V)$ . Choose an ordering  $B = (v_1, v_2, \dots, v_n)$  of the eigenvectors of  $T$ , corresponding to the eigenvalues  $\lambda_1, \lambda_2, \dots, \lambda_n$ . Then  $[T]_B$ , the diagonalization of  $T$ , the matrix of  $T$  with respect to  $B$ , is

$$\begin{bmatrix} \lambda_1 & 0 & \dots & 0 \\ 0 & \lambda_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \lambda_n \end{bmatrix}$$

### 7.6.3 Powers of a diagonalizable operator

**Lemma.** If  $v$  is an eigenvector of  $T$  with eigenvalue  $\lambda$  and  $n$  is a positive integer, then  $T^n v = \lambda^n v$ .

**Lemma.** If  $T$  is diagonalizable, then there exists an invertible matrix  $P$  such that the diagonalization of  $T$  is equal to

$$D = P[T]P^{-1}$$

(where  $[T]$  is with respect to the standard basis)

Furthermore, for any positive integer  $n$ ,

$$[T]^n = P^{-1} D^n P$$

One example of a  $P$  that satisfies this equation is the change-of-basis matrix from the basis of  $[T]$  to the basis of  $D$

**Procedure (Power of a diagonal matrix).** Let  $D$  be a diagonal matrix equal to

$$\begin{bmatrix} \lambda_1 & 0 & \dots & 0 \\ 0 & \lambda_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \lambda_n \end{bmatrix}$$

Then  $D^n$  is equal to

$$\begin{bmatrix} \lambda_1^n & 0 & \dots & 0 \\ 0 & \lambda_2^n & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \lambda_n^n \end{bmatrix}$$

7.7 Inner product spaces

7.7.1 Inner product

Trimm 7.1

*Definition of Positive definite.* A map  $f : V \times V \rightarrow F$  is positive definite iff for any  $v \in V$  where  $v \neq 0$ ,

$$f(v, v) > 0$$

and  $f(0, 0) = 0$ .

*Definition of Inner product on a real vector space.* Let  $V$  be a real vector space. Then an inner product on  $V$  is a positive definite symmetric bilinear form on  $V$ .

The inner product of  $v, w \in V$  is denoted  $(v, w)$ .

*Definition of Dot product on  $\mathbb{R}^n$ .* The dot product is the mapping that maps  $x, y \in \mathbb{R}^n$  to the real number

$$x \cdot y = \sum_{i=1}^n x_i y_i$$

It is an inner product on  $\mathbb{R}^n$ , and satisfies the following properties for any  $v, w, x \in V$ :

- $(cv + w) \cdot x = cv \cdot x + w \cdot y$
- $v \cdot w = w \cdot v$
- $x \cdot (cv + w) = cx \cdot v + x \cdot w$
- $|v| = \sqrt{v \cdot v}$

*Definition of Complex conjugate.* The complex conjugate of the complex number  $a + bi$  is

$$\overline{a + bi} = a - bi$$

*Definition of Conjugate-linear map.* A map  $f : V \rightarrow W$  where  $V$  and  $W$  are complex vector spaces is conjugate-linear iff for all  $x, y \in V, s \in \mathbb{C}$ ,

- **Additivity:**  $f(x + y) = f(x) + f(y)$
- **Conjugate homogeneity:**  $f(sx) = \overline{s}f(x)$

A conjugate-linear map is a type of **semilinear map**.

*Definition of Sesquilinear map.* A map  $f : V \times V \rightarrow W$  which is linear in the first argument and semilinear in the second argument.

Iff it is conjugate-linear in the second argument, for all  $z_1, z_2 \in \mathbb{C}^n, c \in \mathbb{C}$ ,

$$f(w, cz_1 + z_2) = \overline{c}f(w, z_1) + f(w, z_2)$$

*Definition of Inner product on a complex vector space.* Let  $V$  be a complex vector space. Then an inner product on  $V$  is a positive-definite sesquilinear form on  $V$ .

*Definition of Dot product on  $\mathbb{C}^n$ .* The dot product is the mapping that maps  $z, w \in \mathbb{C}^n$  to the complex number

$$z \cdot w = \sum_{i=1}^n z_i \overline{w_i}$$

It is an inner product on  $\mathbb{C}^n$ , and satisfies the following properties for any  $v, w, x \in V$ :

- $(cv + w) \cdot x = cv \cdot x + w \cdot y$
- $v \cdot w = \overline{w \cdot v}$
- $x \cdot (cv + w) = \overline{c}x \cdot v + x \cdot w$
- $|v| = \sqrt{v \cdot v}$

*Definition of Inner product space.* A vector space  $V$  together with an inner product on  $V$ .

7.7.2 Orthogonality

Trimm 7.1

For this section, let  $V$  be an inner product space.

*Definition of Orthogonality.* Two vectors  $u, v \in V$  are orthogonal iff  $(u, v) = 0$ .

**Lemma.**  $0$  is orthogonal to all vectors.

**Pythagorean Theorem.** If  $u, v \in V$  are orthogonal, then

$$|u + v|^2 = |u|^2 + |v|^2$$

**Theorem (Orthogonal decomposition).** Let  $u, v \in V$ . Then  $u$  can be uniquely decomposed as

$$u = u_{\parallel} + u_{\perp}$$

where  $u_{\parallel} \parallel v$  and  $u_{\perp} \perp v$ .

**Theorem.** For all  $u, v \in V$ ,

- **Cauchy-Schwarz inequality:**  $|(u, v)| \leq |u||v|$
- **Triangle Inequality:**  $|u + v| \leq |u| + |v|$
- **Reverse Triangle Inequality:**  $||u| - |v|| \leq |u - v|$
- **Parallelogram Law:**  $|u + v|^2 + |u - v|^2 = 2(|u|^2 + |v|^2)$

# Differential Equations (8)

A *differential equation* is an equation involving a quantity and one or more of its derivatives.

## 1 Ordinary Differential Equations

An ODE involves the derivative of the dependent variable with respect to a single independent variable.

### 8.0.1 Solving by Integration

**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

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

### 8.0.2 Initial-Value Problems

**Definition of Initial-Value problem.** Assuming the function  $f$  is continuous, then the function  $y$  is a solution of the IVP given that

$$\frac{dy}{dx} = f(x, y), y(x_0) = y_0,$$

Where  $x_0$  is called the *initial point* for the IVP and  $y_0$  is the *initial value*.

### 8.0.3 Existence and Uniqueness of Solutions

**Theorem (Existence and Uniqueness).** If  $f$  is continuous, then the function  $f$  as previously defined has at least one solution on the interval of continuity. If at least one solution exists and  $\frac{\partial f}{\partial y}$  is continuous on the same interval, the solution is unique.

### 8.0.4 Autonomous Equations

**Definition of Autonomous Equation.** An autonomous equation is an equation where the derivative of the dependent variable can be expressed as a function of the dependent variable alone, assuming continuity.

An example of an autonomous equation is

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

Whereas

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

Is not autonomous.

Since  $f(y)$  is independent of  $x$ , the resulting slope field has translational symmetry across the  $x$ -axis. A snapshot of the slope field through a vertical line  $x = x_0$  is called a *phase line*. A line where the direction of the slopes is indicated with arrows either going down or up is called a *one-dimensional phase portrait* of the autonomous ODE.

At  $y$  values where  $f(y) = 0$ , when the slope is zero, those points are called *equilibrium points* or *stationary points*.

1. If surrounding solutions approach  $y = y_0$  asymptotically then the equilibrium point is *asymptotically stable* or an *attractor*.
2. If surrounding solutions move away from  $y = y_0$  then the equilibrium point is *unstable* or a *repeller*.
3. If surrounding solutions approach from one side and repel from another then the equilibrium point is *semi-stable*.

### 8.0.5 Bifurcations

A differential equation that depends on a parameter *bifurcates* if there is a qualitative change in the solutions as parameter changes, meaning that the phase line changes.

We can see this change in phase line by plotting the parameter and the solution of the differential equation. The resulting graph would look like an array of phase lines. Each point on the phase lines is called a *bifurcation point*.

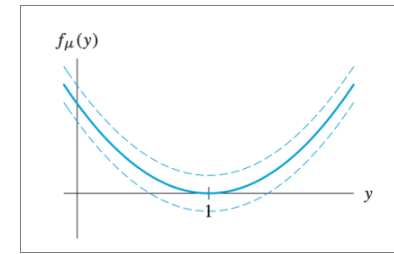


Figure: Graph of  $f_\mu(y) = y^2 - 2y + \mu$  for  $\mu < 1$ ,  $\mu = 1$ , and  $\mu > 1$ .

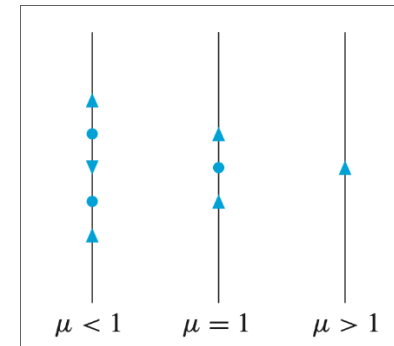


Figure: Corresponding phase portraits for  $\frac{dy}{dx} = y^2 - 2y + \mu$ .

The typical way to visualize bifurcations is through *bifurcation diagrams*. The parabola on the following figure is called a *bifurcation line*.

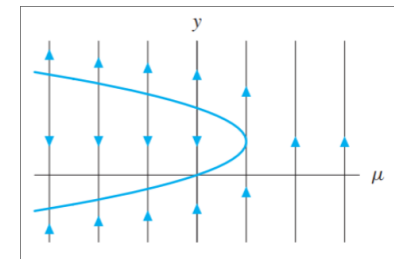


Figure: Bifurcation diagram for  $\frac{dy}{dx} = y^2 - 2y + \mu$ .

### 8.0.6 Separable Equations

**Definition of Separable first-order ODE.** An ODE is separable if it can be expressed as

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

where  $g$  and  $h$  are continuous.

We can simplify the process of solving a separable equations by defining the following where  $H(y)$  and  $G(x)$  are antiderivatives of  $\frac{1}{h(y)}$  and  $g(x)$ , respectively, and  $c \in \mathbb{R}$  is an arbitrary constant.

$$H(y) = G(x) + c$$

which can then be expressed as

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

### 8.0.7 Implicitly-Defined Solutions

Sometimes a separable equation can't be solved for  $y$  explicitly. Let's define  $F(x, y)$  as

$$F(x, y) := H(y) - G(x) - c$$

so that

$$F(x, y) = 0$$

The equation above implicitly defines  $y$  as a function of  $x$  only if it follows the *Implicit Function Theorem* from Multivariable Calculus.

**Theorem (Implicit Function Theorem).** If  $F$  is defined on a disc containing  $(x_0, y_0)$ , where

1.  $F(x, y) = 0$
2.  $\frac{\partial F}{\partial x}$  and  $\frac{\partial F}{\partial y}$  are continuous on the disc
3.  $\frac{\partial F}{\partial x} \neq 0$

then the equation  $F(x, y) = 0$  defines  $y$  as a function of  $x$  on some open set containing the point  $(x_0, y_0)$ .

### 8.0.8 Singular Solutions

**Definition of Singular Solution.** A solution is singular if it cannot be obtained by any choice of  $c$  in the solution equation of the separable ODE.

When either  $h(y)$  or  $g(x)$  are equal to 0 inside a separable equation, then they would be valid solutions, but may not show up in the integration method for finding solutions as defined in the Separable Equations section. If that is the case, then those solutions are unique.

### 8.0.9 Orthogonal Trajectories

An *orthogonal trajectory* of a family of curves is a curve that intersects each curve of the family orthogonally.

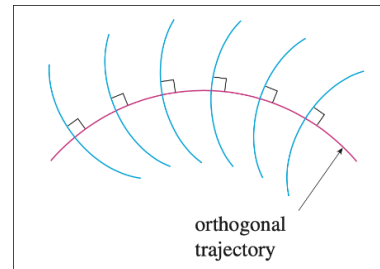


Figure: An example of an orthogonal trajectory.

For example,

$$x^2 + y^2 = r^2$$

and

$$y = mx$$

are orthogonal trajectories of each other.

To find orthogonal trajectories of an equation in terms of  $x$ ,  $y$ , and another constant variable:

1. Take derivative of both sides in respect to  $x$
2. Solve for  $\frac{dy}{dx}$  from previous equation
3. Use the original equation to eliminate the constant and write an expression that only depends on  $x$  and  $y$
4. The previous equation is a slope  $m(x, y)$ ; find the orthogonal slope at point  $(x, y)$
5. Solve the differential equation  $\frac{dy}{dx} = m(x, y)$  to find the family of orthogonal trajectories

### 8.0.10 Linear Equations

**Definition of Linear Equation.** An equation is linear if it can be expressed in the form

$$\frac{dy}{dx} = p(x)y + q(x)$$

where  $p, q : (a, b) \rightarrow \mathbb{R}, -\infty \leq a < b \leq \infty$  are continuous.

If  $q(x) = 0$ , then the linear equation is called *homogeneous*. If  $p(x)$  is a constant, but not necessarily  $q(x)$ , it is called *constant-coefficient*.

### 8.0.11 Variation of Parameters

If  $y_h(x)$  is a solution of a homogeneous linear equation, then  $cy_h(x)$  is also a solution of the same homogeneous equation. A general solution of a homogeneous linear equation is

$$y_h(x) = ce^{\int p(x) dx}$$

A general solution of nonhomogeneous linear equation is

$$y(x) = ce^{\int p(x) dx} + e^{\int p(x) dx} \int e^{-\int p(x) dx} q(x) dx$$

### 8.0.12 Integrating Factors

This can be simplified by defining

$$\mu(x) := e^{-\int p(x) dx}$$

$$y(x) = \frac{1}{\mu(x)} \int \mu(x) q(x) dx$$

### 8.0.13 Singular Points

If we represent a linear equation in the form

$$a_1(x) \frac{dy}{dx} + a_0(x)y = g(x)$$

and divide both sides by  $a_1(x)$ , then  $p$  and  $q$  will be discontinuous when  $a_1(x) = 0$ . These points are called *singular points*. These discontinuous points carry over to the final solution.

### 8.0.14 Bernoulli's Equation

An ODE in the form

$$\frac{dy}{dx} = p(x)y + f(x)y^n$$

where  $n \in \mathbb{R}$ , is called *Bernoulli's equation*.

This equation is linear if  $n = 0, 1$ . By substituting  $u = y^{1-n}$ , the equation can be rewritten in a linear form as

$$\frac{du}{dx} = (1-n)(p(x)u + q(x))$$

where  $n \neq 0, 1$ .

8.0.15 Exact Equations

An exact equation is a differential equation in the form

$$M(x, y) + N(x, y) \frac{dy}{dx} = 0$$

where  $M, N$  are continuously differentiable. They also represent partial derivatives of the potential function  $\psi$

$$\psi_x + \psi_y \frac{dy}{dx} = 0$$

where  $\psi(x, y)$  is an existing *potential function*, as seen in Multivariable Calculus. The equation is exact only if,

- $\psi_{xy} = \psi_{yx}$
- Domain of functions above is open and topologically simply-connected (continuous)

So if the potential function exists, then the solution to the equation would be

$$\psi(x, y) = 0$$

8.0.16 Homogeneous Equations

A real-valued function is *homogeneous of degree  $\alpha$*  if it can be rewritten in the form

$$f(tx, ty) = t^\alpha f(x, y)$$

where  $\alpha, t \in \mathbb{R}$ .

A first-order differential equation of the form

$$M(x, y) + N(x, y) \frac{dy}{dx} = 0$$

is called *homogeneous* if both  $M$  and  $N$  are homogeneous of the same degree. To solve it, simply remember the substitution

$$y = ux$$

8.0.17  $n$ th-Order Linear Equations

An  $n$ th-order differential equation is in the form

$$a_n(x) \frac{d^n y}{dx^n} + a_{n-1}(x) \frac{d^{n-1} y}{dx^{n-1}} + \cdots + a_1(x) \frac{dy}{dx} + a_0(x)y = g(x)$$

where the functions  $a_i, g : (a, b) \rightarrow \mathbb{R}$  are continuous. An  $n$ th-order *initial value problem* (IVP) is to find the solution of the equation above where  $x_0$  on interval  $I$  is subject to  $n$  initial conditions

$$y(x_0) = y_0, \quad y'(x_0) = y_1, \quad \dots, \quad y^{n-1}(x_0) = y_{n-1}$$

**Theorem.** If  $a_n(x) \neq 0$  on  $I$  and  $x_0 \in I$ , then a solution  $y$  of the  $n$ th-order IVP exists on  $I$  and is unique.

8.0.18 Boundary Value Problems

A boundary value problem (BVP) is when a linear differential equation of order two or greater has the dependent variable  $y$  or its derivatives specified at different points. E.g.  $y(a) = y_0, y(b) = y_1$ . Those values are called *boundary conditions*. A solution to this BVP would satisfy the differential equation on  $I$ , whose graph passes through  $(a, y_0)$  and  $(b, y_1)$ . Those boundary conditions can be often written as

$$\begin{aligned} \alpha_1 y(a) + \beta_1 y'(a) &= \gamma_1, \\ \alpha_2 y(a) + \beta_2 y'(a) &= \gamma_2, \end{aligned}$$

where  $\alpha_1, \alpha_2, \beta_1, \beta_2, \gamma_1, \gamma_2$  are arbitrary constants. Conclusions of the earlier defined theorem regarding IVP for  $n$ th-order equations does not apply to BVP.

8.0.19 Homogeneous ( $n$ th-Order Linear) Equations

An  $n$ th-order linear differential equation is homogeneous if  $g(x)$  in

$$a_n(x) \frac{d^n y}{dx^n} + a_{n-1}(x) \frac{d^{n-1} y}{dx^{n-1}} + \cdots + a_1(x) \frac{dy}{dx} + a_0(x)y = g(x)$$

is equal to zero. First the associated homogeneous equation has to be solved before solving the nonhomogeneous equation.

8.0.20 Differential Operators

The symbol  $D$  is the *differential operator*, where

$$D^n y = \frac{d^n y}{dx^n}.$$

The  $n$ -th order *differential operator* or *polynomial operator* is

$$L = a_n(x)D^n + a_{n-1}(x)D^{n-1} + \cdots + a_1(x)D + a_0(x)$$

Using  $L$ ,  $n$ th-order linear equations can be written as

$$Ly = 0 \quad \text{and} \quad Ly = g(x)$$

The operator is also linear so it has the property

$$L(c_1 f(x) + c_2 g(x)) = c_1 Lf(x) + c_2 Lg(x)$$

**Theorem (Superposition Principle for Homogeneous Linear Equations).** Let  $y_1, \dots, y_k$  be solution of  $Ly = 0$  on interval  $I$ . Then the linear combination

$$y = c_1 y_1 + \cdots + c_k y_k$$

where  $c_i$  are constants, is also a solution of  $Ly = 0$ .

By this theorem, every homogeneous  $n$ th-order linear equation has a solution of  $y = 0$ .

8.0.21 Linear Dependence and Independence

**Definition of Linear Dependence.** A set of functions is *linearly dependent* on interval  $I$  if there exists constants  $c_i$ , not all zero, where

$$c_1 f_1(x) + \cdots + c_n f_n(x) = 0$$

for all  $x$  in  $I$ . If the only constants for which the equation above is satisfied are

$$c_1 = c_2 = \cdots = c_n = 0$$

then the set is *linearly independent*.

**Definition of Wronskian.** Given that each function in  $f_1, \dots, f_n$  is at least  $n - 1$  times differentiable, the determinant

$$W(f_1, f_2, \dots, f_n) = \begin{vmatrix} f_1 & f_2 & \cdots & f_n \\ f_1' & f_2' & \cdots & f_n' \\ \vdots & \vdots & \ddots & \vdots \\ f_1^{(n-1)} & f_2^{(n-1)} & \cdots & f_n^{(n-1)} \end{vmatrix}$$

is called the *Wronskian* of the functions.

The set of solutions  $y_1, y_2, \dots, y_n$  on interval  $I$  for a homogeneous equation is linearly independent only if  $W(y_1, y_2, \dots, y_n) \neq 0$  on  $I$ .

This linearly independent set of solutions is called the *fundamental set of solutions* on the specified interval.

**Theorem (Existence of a Fundamental Set).** If functions  $a_i, g$  are continuous on some common interval  $I$ , and  $a_n(x) \neq 0$  on  $I$ , then there exists a fundamental set of solutions of the homogeneous linear  $n$ th-order differential equation.

Given that  $y_1, y_2, \dots, y_n$  is the fundamental set of solutions for the homogeneous equation on  $I$ , then its general solution is

$$y = c_1 y_1(x) + c_2 y_2(x) + \cdots + c_n y_n(x)$$

where  $c_i$  are arbitrary real constants.

Any function  $y_p$ , free of arbitrary parameters, that satisfies the nonhomogeneous equation, is said to be the *particular solution* of the equation.

**Theorem.** The general solution of the  $n$ th-order nonhomogeneous equation is of the form

$$y(x) = y_p(x) + c_1 y_1(x) + c_2 y_2(x) + \cdots + c_n y_n(x)$$

where  $y_p$  is the particular solution and  $y_1, \dots, y_n$  are a fundamental set of solutions of the associated homogeneous equation.

8.0.22 Reduction of Order

Reduction of order is a method of substitution to reduce a homogeneous second order equation to a first order equation. This can be used to find a second nontrivial solution using the first and create a fundamental set of solutions.

$$y_2(x) = y_1(x) \int \frac{e^{-\int P(x)dx}}{y_1^2(x)} dx$$

where the original equation is in the standard form

$$y'' + P(x)y' + Q(x)y = 0$$

8.0.23 Reduction of order for nonhomogeneous equations

The equation

$$y_p(x) = y_1(x) \left[ \int \frac{e^{-\int P(x)dx}}{(y_1(x))^2} \left[ \int e^{\int P(x)dx} y_1(x) R(x) dx \right] dx \right]$$

can be used to find the particular solution needed for general equation, as mentioned in the previous section, of the nonhomogeneous standard equation

$$y'' + P(x)y' + Q(x)y = R(x)$$

8.0.24 Solving first-order constant coefficient equations

To solve a first-order constant coefficient equation, an algebraic method can be used where in

$$ay' + by = 0$$

where  $a, b$  are constants. A general solution would be in the form

$$y = e^{-\frac{b}{a}x}$$

8.0.25 Solving second-order constant coefficient equations

To solve a second-order constant coefficient equation,

$$ay'' + by' + cy = 0$$

find the two solutions  $m_1$  and  $m_2$  in,

$$am^2 + bm + c = 0$$

using the quadratic formula,

$$m_1, m_2 = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

If the discriminant  $b^2 - 4ac > 0$ , the general solution would be,

$$y = c_1 e^{m_1 x} + c_2 e^{m_2 x}$$

otherwise, if the discriminant is zero (i.e.  $m_1 = m_2$ ), the first solution would be,

$$y_1 = e^{m_1 x}$$

where the general solution can be found by finding  $y_2$  using reduction of order.

If the discriminant is negative and the solution is two conjugates in the form,

$$m_1 = \alpha + i\beta$$

$$m_2 = \alpha - i\beta$$

Then the fundamental set of solutions can be written using Euler's formula,

$$y = c_1 e^{\alpha x} \cos(\beta x) + c_2 e^{\alpha x} \sin(\beta x)$$

8.0.26 Solving higher-order constant coefficient equations

First, the auxiliary  $n$ th-degree polynomial equation must be solved,

$$a_n m^n + a_{n-1} m^{n-1} + \dots + a_1 m + a_0 = 0$$

Then, higher-order constant coefficient equations with real solutions extend the same way where,

$$y = c_1 e^{m_1 x} + c_2 e^{m_2 x} + \dots + c_n e^{m_n x}$$

But if any real root would have a multiplicity of  $k > 1$ , then for each multiplicity,

$$e^{m_1 x}, x e^{m_1 x}, \dots, x^{k-1} e^{m_1 x}$$

are additional linearly independent solutions in the fundamental set. The same pattern extends for complex roots,

$$e^{\alpha x} \cos(\beta x), x e^{\alpha x} \cos(\beta x), \dots, x^{k-1} e^{\alpha x} \cos(\beta x)$$

$$e^{\alpha x} \sin(\beta x), x e^{\alpha x} \sin(\beta x), \dots, x^{k-1} e^{\alpha x} \sin(\beta x)$$

8.0.27 Annihilation operators

Recall the form  $Ly = g(x)$ . Assuming coefficients are constant and if  $r_1$  is a root of the auxiliary equation,

$$a_n m^n + a_{n-1} m^{n-1} + \dots + a_1 m + a_0 = 0$$

then  $L = (D - r_1)P(D)$ , where the polynomial expression  $P(D)$  is a linear differential operator of order  $n - 1$ .

For example, the expression,

$$y'' + 4y' + 4y = 0$$

can be represented as

$$L = D^2 + 4D + 4 = (D + 2)^2$$

$$Ly = 0$$

*Definition of Annihilation of a function.* If  $L$  is a linear differential operator with constant coefficients such that  $L(f(x)) = y$ , then  $L$  is the *annihilator* of the function.

- $y = k$  is annihilated by  $D$
- $y = x^{n-1} + x^{n-2} + \dots + c_0$  is annihilated by  $D^n$
- $y = x^{n-1} e^{\alpha x} + \dots + e^{\alpha x}$  is annihilated by  $(D - \alpha)^n$
- $y = x^{n-1} e^{\alpha x} \cos(\beta x) + \dots + e^{\alpha x} \cos(\beta x)$  is annihilated by  $(D^2 - 2\alpha D + (\alpha^2 + \beta^2))^n$
- $y = x^{n-1} e^{\alpha x} \sin(\beta x) + \dots + e^{\alpha x} \sin(\beta x)$  is annihilated by  $(D^2 - 2\alpha D + (\alpha^2 + \beta^2))^n$

If  $L_1$  annihilates  $y_1$  and  $L_2$  annihilates  $y_2$ , then the (commutative) product  $L_1 L_2$  annihilates any linear combination  $c_1 y_1 + c_2 y_2$ . This also implies that the annihilator is not unique.

8.0.28 Method of undetermined coefficients

This method can be used to solve equations in the form

$$Ly = g(x)$$

where all coefficients are constant and  $g(x)$  is a linear combination of

$$k, x^m, x^m e^{\alpha x}, x^m e^{\alpha x} \cos(\beta x), x^m e^{\alpha x} \sin(\beta x)$$

and  $m$  is nonnegative integer and  $\alpha, \beta \in \mathbb{R}$ .

If  $g(x)$  can be annihilated by  $L_1$ , then applying it to both sides gives

$$L_1 Ly = L_1(g(x)) = 0$$

then solving for  $L_1 Ly = 0$  can yield the general form of a particular solution  $y_p$  of the nonhomogeneous equation. Then substituting it into  $Ly = g(x)$  will yield an explicit particular solution.

For example, to solve

$$y'' + 3y' + 2y = 4x^2$$

first find the auxiliary form of associated homogeneous equation

$$m^2 + 3m + 2 = (m + 1)(m + 2) = 0$$

and find the general solution using it

$$y = c_1 e^{-1x} + c_2 e^{-2x}$$

Then find  $L_1$  that annihilates  $g(x)$

$$L_1 = D^3$$

$$D^3(4x^2) = 0$$

So

$$L_1 Ly = D^3(D + 1)(D + 2) = 0$$

Now turn it into an auxiliary equation and solve for roots (including multiplicity above 1)

$$\begin{aligned} m^3(m+1)(m+2) &= 0 \\ m_1 = m_2 = m_3 &= 0 \\ m_4 &= -1 \\ m_5 &= -2 \end{aligned}$$

Use those solutions to create a general solution

$$y = c_1 + c_2x + c_3x^2 + c_4e^{-1x} + c_5e^{-2x}$$

Since we know that the last two terms  $c_4e^{-1x} + c_5e^{-2x}$  are the solution of the associated homogeneous equation, the rest must include the particular solution

$$y_p = c_1 + c_2x + c_3x^2$$

You can substitute derivatives of it into the original nonhomogeneous equation and solve for the constants

$$\begin{aligned} y_p' &= c_2 + 2c_3x \\ y_p'' &= 2c_3 \\ y_p'' + 3y_p' + 2y_p &= 4x^2 \\ (2c_3) + 3(c_2 + 2c_3x) + 2(c_1 + c_2x + c_3x^2) &= 4x^2 \end{aligned}$$

Collect like terms and create a system of equations

$$\begin{aligned} (2c_3 + 3c_2 + 2c_1) + x(6c_3 + 2c_2) + x^2(2c_3 - 4) &= 0 \\ 2c_3 + 3c_2 + 2c_1 &= 0 \\ 6c_3 + 2c_2 &= 0 \\ 2c_3 - 4 &= 0 \end{aligned}$$

Therefore the general solution and final answer will be

$$y = c_1e^{-x} + c_2e^{-2x} + 7 - 6x + 2x^2$$

8.0.29 Variation of parameters for second-order equations

**Theorem (Cramer’s Rule).** Let  $A$  be an invertible  $n \times n$  matrix. For any  $b \in \mathbb{R}^n$ , the linear system  $Ax = b$  has the unique solution

$$x_i = \frac{\det A_i(b)}{\det A}, i = 1, 2, \dots, n$$

where  $A_i(b)$  is the matrix obtained from  $A$  by replacing the  $i$ th column of  $A$  by the vector  $b$ .

Using variation of parameters, the particular solution of nonhomogeneous linear equation in the form  $y'' + P(x)y' + Q(x)y = R(x)$  can be found by

$$y_p(x) = y_1(x) \int \frac{-y_2(x)R(x)}{W} dx + y_2(x) \int \frac{y_1(x)R(x)}{W} dx$$

where  $W$  is the wronskian

$$W(y_1, y_2) = \begin{vmatrix} y_1 & y_2 \\ y_1' & y_2' \end{vmatrix}$$

So the general solution is

$$y = c_1y_1(x) + c_2y_2(x) + y_p$$

8.0.30 Variation of parameters for higher-order equations

TODO

8.0.31 Cauchy-Euler Equation

*Definition of Cauchy-Euler Equation.* An equation in the form

$$a_nx^ny^n + a_{n-1}x^{n-1}y^{n-1} + \dots + a_1xy' + a_0 = g(x)$$

on  $(0, \infty)$  where  $a_n$  coefficients are constant, is known as a *Cauchy-Euler equation*. To find solutions on  $(-\infty, 0)$ , substitute  $u = -x$ .

You can solve Cauchy-Euler equations with the substitution  $x = e^t$ , which reduces it to an equation with constant coefficients, then substitute it back with  $t = \ln(x)$ .

$$\begin{aligned} z(t) &= e^t \\ y'(x) &= y'(e^t)e^t = z'(t) \\ y''(x) &= y''(e^t)e^{2t} = z''(t) \end{aligned}$$

So

$$a_2x^2y'' + a_1xy' + a_0 = g(x)$$

Turns into

$$a_2z''(t) + a_1z'(t) + a_0 = g(e^t)$$

8.0.32 Ordinary and singular points

In the standard second-order homogeneous equation

$$y'' + P(x)y' + Q(x)y = 0$$

A point  $x_0$  is an *ordinary point* if both  $P(x)$  and  $Q(x)$  are analytic at  $x_0$ .

A function  $f$  is analytic at a point  $x_0$  if it can be represented by a power series in  $x - x_0$  with a positive or infinite radius of convergence. For example functions like  $e^x$  or  $\sin(x)$  that can be represented with a Taylor series are analytic at any  $x_0 \in \mathbb{R}$ .

All points that are not ordinary are *singular points* of the equation.

**Theorem (Existence of Power Series Solutions).** If  $x_0$  is an ordinary point, there exists a fundamental set of solutions in the form of power series centered at  $x_0$ , each of which converges at least on  $|x - x_0| < R$ , where  $R$  is the distance in complex plane from  $x_0$  to the nearest singular point.

For example in the equation

$$(x^2 - 1)y'' + 2xy' + 6y = 0$$

At ordinary point  $x = 0$ ,  $R = 1$  since  $x_0 = \pm i$  are the singular points and distance between  $x$  and  $x_0$  is 1.

8.0.33 Power series solutions

A simple equation

$$y' - y = 0$$

can be represented with power series with

$$\begin{aligned} y &= \sum_{n=0}^{\infty} c_nx^n \\ y' &= \sum_{n=1}^{\infty} nc_nx^{n-1} \\ \sum_{n=1}^{\infty} nc_nx^{n-1} - \sum_{n=0}^{\infty} c_nx^n &= 0 \end{aligned}$$

These series can be combined into

$$\sum_{n=0}^{\infty} ((n+1)c_{n+1} - c_n)x^n = 0$$

which implies that

$$(n+1)c_{n+1} - c_n = 0, n \geq 0$$

that can be rearranged into

$$c_{n+1} = \frac{c_n}{n+1}$$

and converted to non-recursive form

$$c_n = \frac{c_0}{n!}$$

The result can be plugged back in, meaning that the final solution is

$$y = c_0 \sum_{n=0}^{\infty} \frac{x^n}{n!} = c_0e^x$$



8.0.34 Laplace Transform

The Laplace transform can be defined as,

$$\mathcal{L}\{f(t)\} = \int_0^\infty e^{-st} f(t) dt$$

given that  $t \geq 0$  and the integral converges. The result should be a function of  $s$ . Typically, transformed functions are denoted with their corresponding capital letter, for example,

$$\mathcal{L}\{f(t)\} = F(s)$$

Common Laplace transforms include,

$$\begin{aligned}\mathcal{L}\{1\} &= \frac{1}{s} \\ \mathcal{L}\{t^n\} &= \frac{n!}{s^{n+1}} \\ \mathcal{L}\{e^{at}\} &= \frac{1}{s-a} \\ \mathcal{L}\{\sin(kt)\} &= \frac{k}{s^2 + k^2} \\ \mathcal{L}\{\cos(kt)\} &= \frac{s}{s^2 + k^2}\end{aligned}$$

Since Laplace transform is a linear function, it satisfies the following,

$$\mathcal{L}\{\alpha f(t) + g(t)\} = \alpha \mathcal{L}\{f(t)\} + \mathcal{L}\{g(t)\}$$

To apply a Laplace transform on a piecewise function, simply split the integral into as many parts as necessary.

The Laplace transform is 1 to 1 on set of functions that are continuous on  $[0, \infty)$  and does not grow faster than  $Me^{ct}$

8.0.35 Solving ODE IVPs with Laplace transform

The Laplace transform can be used on derivatives as well,

$$\begin{aligned}\mathcal{L}\{f'(t)\} &= s\mathcal{L}\{f(t)\} - f(0) \\ \mathcal{L}\{f''(t)\} &= s^2\mathcal{L}\{f(t)\} - sf(0) - f'(0)\end{aligned}$$

Which can be used to solve linear ODE IVPs. For instance,

$$\begin{aligned}a_2y'' + a_1y' + a_0y &= g(t) \\ y(0) &= y_0, \quad y'(0) = y'_0\end{aligned}$$

By taking Laplace transform of both sides, the solution of the equation would be,

$$y(t) = \mathcal{L}^{-1}\left\{\frac{G(s) + a_2y_0s + a_2y'_0 + a_1y_0}{a_2s^2 + a_1s + 1}\right\}$$

8.0.36 Laplace transform translations

**Theorem (First Translation Theorem).** If  $\mathcal{L}\{f(t)\} = F(s)$  and  $a \in \mathbb{R}$ , then,

$$\mathcal{L}\{e^{at}f(t)\} = F(s-a)$$

Which can also be denoted by,

$$\mathcal{L}\{e^{at}f(t)\} = \mathcal{L}\{f(t)\}|_{s \rightarrow s-a}$$

The unit step function can be defined as,

$$\mathcal{U}(t-a) = \begin{cases} 0, & 0 \leq t \leq a, \\ 1, & t \geq a \end{cases}$$

**Theorem (Second Translation Theorem).** Given the function,

$$f(t-a)\mathcal{U}(t-a) = \begin{cases} 0, & 0 \leq t \leq a, \\ f(t-a), & t \geq a \end{cases}$$

And if  $a > 0$ , then,

$$\mathcal{L}\{f(t-a)\mathcal{U}(t-a)\} = e^{-as}F(s)$$

The theorem can also be applied in inverse form,

$$\mathcal{L}^{-1}\{e^{-as}F(s)\} = f(t-a)\mathcal{U}(t-a)$$

8.0.37 Derivatives of a transform

$$\mathcal{L}\{tf(t)\} = -\frac{d}{ds}\mathcal{L}\{f(t)\}$$

Which can be extended to,

$$\mathcal{L}\{t^n f(t)\} = (-1)^n \frac{d^n}{ds^n} \mathcal{L}\{f(t)\}$$

8.0.38 The convolution theorem

If  $f$  and  $g$  are piecewise continuous functions on the interval  $[0, \infty)$ , then the convolution of  $f$  and  $g$ , denoted  $f * g$ , is the function,

$$f * g = \int_0^t f(\tau)g(t-\tau)d\tau$$

Note that convolution is a commutative operation.

**Theorem (Convolution Theorem).** If  $f, g$  fit convolution criteria and are of exponential order, then,

$$\mathcal{L}\{f * g\} = F(s)G(s)$$

8.0.39 Transform of an integral

$$\mathcal{L}\left\{\int_0^t f(\tau)d\tau\right\} = \frac{F(s)}{s}$$

8.0.40 Volterra integral equation

A Volterra integral equation for  $f(t)$  is an equation in the form,

$$f(t) = g(t) + \int_0^t f(\tau)h(t-\tau)d\tau$$

Where  $g(t)$  and  $h(t)$  are known.

8.0.41 Transform of a periodic function

**Theorem (Transform of a Periodic Function).** If  $f(t)$  is piecewise continuous on  $[0, \infty)$  of exponential order and periodic with period  $T$ , then,

$$\mathcal{L}\{f(t)\} = \frac{1}{1-e^{-sT}} \int_0^T e^{-st} f(t) dt$$