Comprehensive Compendium:
Calculus II

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August 28,2023
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Contents

Calculus II

1.1   Chapter 1 Definitions and Theorems

- **Mean Value Theorem For Integrals**: If $f(x)$ is continuous over an interval [a,b], then there is at least one point $c \in [a, b]$ such that

$$f(c) = \frac{1}{b-a} \int f(x) \, dx.$$

- **Integrals resulting in inverse trig functions**

  1.

$$\int \frac{dx}{\sqrt{a^2 - x^2}} = \sin^{-1} \frac{x}{|a|} + C.$$

  2.

$$\int \frac{dx}{a^2 + x^2} = \frac{1}{a} \tan^{-1} \frac{x}{a} + C.$$

  3.

$$\int \frac{dx}{x\sqrt{x^2 - a^2}} = \frac{1}{|a|} \sec^{-1} \frac{|x|}{a} + C.$$

1.2   Chapter 2 Definitions and Theorems

- **Area between two curves, integrating on the x-axis**

$$A = \int_a^b [f(x) - g(x)] \, dx \tag{1}$$

Where $f(x) \geqslant g(x)$

$$A = \int_a^b [g(x) - f(x)] \, dx.$$

for $g(x) \geqslant f(x)$

- **Area between two curves, integrating on the y-axis**

$$A = \int_c^d [u(y) - v(y)] \, dy \tag{2}$$

- **Areas of compound regions**

$$\int_a^b |f(x) - g(x)| \, dx.$$

- **Area of complex regions**

$$\int_a^b f(x) \, dx + \int_b^c g(x) \, dx.$$

- **Slicing Method**

$$V(s) = \sum_{i=1}^n A(x_i^*) \, \Delta x = \int_a^b A(x) \, dx.$$

- **Disk Method along the x-axis**

$$V = \int_a^b \pi [f(x)]^2 \, dx \tag{3}$$

- **Disk Method along the y-axis**

$$V = \int_c^d \pi [g(y)]^2 \, dy \tag{4}$$

- **Washer Method along the x-axis**

$$V = \int_a^b \pi [(f(x))^2 - (g(x))^2] \, dx \tag{5}$$

- **Washer Method along the y-axis**

$$V = \int_c^d \pi [(u(y))^2 - (v(y))^2] \, dy \tag{6}$$

- **Radius if revolved around other line (Washer Method)**

$$If: \ x = -k$$
$$Then: \ r = Function + k.$$

$$If: \ x = k$$
$$Then: \ r = k - Function.$$

- **Method of Cylindrical Shells (x-axis)**

$$V = \int_a^b 2\pi x f(x) \, dx \tag{7}$$

- **Method of Cylindrical Shells (y-axis)**

$$V = \int_c^d 2\pi y g(y) \, dy \tag{8}$$

- **Region revolved around other line (method of cylindrical shells):**

$$If: \ x = -k$$
$$Then: \ V = \int_a^b 2\pi (x+k)(f(x)) \, dx.$$

$$If: \ x = k$$
$$Then: \ V = \int_a^b 2\pi (k-x)(f(x)) \, dx.$$

- **A Region of Revolution Bounded by the Graphs of Two Functions (method cylindrical shells)**

$$V = \int_a^b 2\pi x \left[f(x) - g(x) \right] \, dx.$$

- **Arc Length of a Function of x**

$$\text{Arc Length} = \int_a^b \sqrt{1 + [f'(x)]^2} \, dx \tag{9}$$

- **Arc Length of a Function of y**

$$\text{Arc Length} = \int_c^d \sqrt{1 + [g'(y)]^2} \, dy \tag{10}$$

- **Surface Area of a Function of x (Around x)**

$$\text{Surface Area} = \int_a^b 2\pi f(x) \sqrt{1 + [f'(x)]^2} \, dx \tag{11}$$

- **Surface Area of a Function of x (Around y)**

$$\text{Surface Area} = \int_a^b 2\pi \sqrt{1 + [f'(x)]^2} \, dx \tag{12}$$

$$\text{Or:} \ \int_a^b 2\pi u(y) \sqrt{1 + (u'(y))^2} \, dy \tag{13}$$

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- **Natural logarithm function**

$$\ln x = \int_1^x \frac{1}{t}\, dt \tag{14}$$

- **Exponential function**

$$y = e^x, \quad \ln y = \ln(e^x) = x \tag{15}$$

- **Logarithm Differentiation**

$$f'(x) = f(x) \cdot \frac{d}{dx} \ln\left(f'(x)\right).$$

Note: Use properties of logs before you differentiate whats inside the logarithm

1.3   Chapter 3 Definitions and Theorems

- **Integration by parts formula**

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

- **Integration by parts for definite integral**

$$\int_a^b u\, dv = uv\Big|_a^b - \int_a^b v\, du$$

- **To integrate products involving sin(ax), sin(bx), cos(ax), and cos(bx), use the substitutions:**

  - **Sine Products**

  $$\sin(ax)\sin(bx) = \frac{1}{2}\cos((a-b)x) - \frac{1}{2}\cos((a+b)x)$$

  - **Sine and Cosine Products**

  $$\sin(ax)\cos(bx) = \frac{1}{2}\sin((a-b)x) + \frac{1}{2}\sin((a+b)x)$$

  - **Cosine Products**

  $$\cos(ax)\cos(bx) = \frac{1}{2}\cos((a-b)x) + \frac{1}{2}\cos((a+b)x)$$

  - **Power Reduction Formula (sine)**

  $$\int \sin^n x\ dx = -\frac{1}{n}\sin^{n-1}x\cos x + \frac{n-1}{n}\int \sin^{n-2}x\ dx$$
  $$\int_0^{\frac{\pi}{2}} \sin^n x\ dx = \frac{n-1}{n}\int_0^{\frac{\pi}{2}} \sin^{n-2}x\ dx.$$

  - **Power Reduction Formula (cosine)**

  $$\int \cos^n x\ dx = \frac{1}{n}\cos^{n-1}x\sin x + \frac{n-1}{n}\int \cos^{n-2}x\ dx$$
  $$\int_0^{\frac{\pi}{2}} \cos^n x\ dx = \frac{n-1}{n}\int_0^{\frac{\pi}{2}} \cos^{n-2}x\ dx.$$

  - **Power Reduction Formula (secant)**

  $$\int \sec^n x\ dx = \frac{1}{n-1}\sec^{n-1}x\sin x + \frac{n-2}{n-1}\int \sec^{n-2}x\ dx$$
  $$\int \sec^n x\ dx = \frac{1}{n-1}\sec^{n-2}x\tan x + \frac{n-2}{n-1}\int \sec^{n-2}x\ dx$$

  - **Power Reduction Formula (tangent)**

  $$\int \tan^n x\, dx = \frac{1}{n-1}\tan^{n-1}x - \int \tan^{n-2}x\, dx$$

- **Trigonometric Substitution**

- $\sqrt{a^2 - x^2}$ use $x = a\sin\theta$ with domain restriction $\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$

- $\sqrt{a^2 + x^2}$ use $x = a\tan\theta$ with domain restriction $\left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$

- $\sqrt{x^2 - a^2}$ use $x = a\sec\theta$ with domain restriction $\left[0, \frac{\pi}{2}\right) \cup \left[\pi, \frac{3\pi}{2}\right)$

- **Steps for fraction decomposition**

  1. Ensure $deg(Q) < deg(P)$, if not, long divide
  2. Factor denominator
  3. Split up fraction into factors
  4. Multiply through to clear denominator
  5. Group terms and equalize
  6. Solve for constants
  7. Plug constants into split up fraction
  8. Compute integral

- **Solving for constants** Either:

  - Plug in values (often the roots)
  - Equalize

- **Cases for partial fractions**

  - Non repeated linear factors
  - Repeated linear factors
  - Nonfactorable quadratic factors

- **Midpoint rule**

$$M_n = \sum_{i=1}^{n} f(m_i)\, \Delta x.$$

- **Absolute error**

$$err = \left| \text{Actual} - \text{Estimated} \right|.$$

- **Relative error**

$$err = \left| \frac{\text{Actual} - \text{Estimated}}{\text{Actual}} \right| \cdot 100\%.$$

- **Error upper bound for midpoint rule**

$$E_M \leqslant \frac{M(b-a)^3}{24n^2}$$

Where M is the maximum value of the second derivative

- **Trapezoidal rule**

$$T_n \frac{1}{2}\Delta x \left(f(x_0) + 2f(x_1) + 2f(x_2) + \cdots + 2f(x_{n-1}) + f(x_n) \right)$$

- **Error upper bound for trapezoidal rule**

$$E_T \leqslant \frac{M(b-a)^3}{12n^2}$$

  Where M is the maximum value of the second derivative

- **Simpson's rule**

$$S_n = \frac{\Delta x}{3}\left(f(x_0) + 4f(x_1) + 2f(x_2) + 4f(x_3) + 2f(x_4) + 4f(x_5) + \cdots + 2f(x_{n-2}) + 4f(x_{n-1}) + f(x_n)\right)$$

- **Error upper bound for Simpson's rule**

$$E_S \leqslant \frac{M(b-a)^5}{180n^4}$$

  Where M is the maximum value of the fourth derivative

- **Finding n with error bound functions**

  1. Find $f''(x)$
  2. Find maximum values of $f''(x)$ in the interval
  3. Plug into error bound function
  4. Set value $\leqslant$ desired accuracy (ex: 0.01)
  5. Solve:
  6. If we were to truncate, we would use the ceil function $\lceil n \rceil$ DO NOT FLOOR

- **Improper integrals (Infinite interval)**

  - $\int_a^{+\infty} f(x)\ dx = \lim\limits_{t \to +\infty} \int_a^t f(x)\ dx$
  - $\int_{-\infty}^b f(x)\ dx = \lim\limits_{t \to -\infty} \int_t^b f(x)\ dx$
  - $\int_{-\infty}^{+\infty} f(x)\ dx = \int_{-\infty}^0 f(x)\ dx + \int_0^{+\infty} f(x)\ dx$

- **Improper integral (discontinuous)**

  - Let $f(x)$ be continuous on $[a,b)$, then;

$$\int_a^b f(x)\ dx = \lim\limits_{t \to b^-} \int_a^t f(x)\ dx\ .$$

  - Let $f(x)$ be continuous on $(a,b]$, then;

$$\int_a^b f(x)\ dx = \lim\limits_{t \to b^+} \int_t^b f(x)\ dx\ .$$

    In each case, if the limit exists, then the improper integral is said to converge. If the limit does not exist, then the improper integral is said to diverge.

  - Let $f(x)$ be continuous on $[a,b]$ except at a point $c \in (a,b)$, then;

$$\int_a^b f(x)\ dx = \int_a^c f(x)\ dx + \int_c^b f(x)\ dx.$$

    If either integral diverges, then $\int_a^b f(x)\ dx$ diverges

- **Comparison theorem** Let $f(x)$ and $g(x)$ be continuous over $[a, +\infty)$. Assume that $0 \leqslant f(x) \leqslant g(x)$ for $x \geqslant a$.

  - If $\int_a^{+\infty} f(x)\,dx = \lim_{t \to +\infty} \int_a^t f(x)\,dx = +\infty$,
    then $\int_a^{+\infty} g(x)\,dx = \lim_{t \to +\infty} \int_a^t g(x)\,dx = +\infty$.
  - If $\int_a^{+\infty} g(x)\,dx = \lim_{t \to +\infty} \int_a^t g(x)\,dx = L$, where L is a real number,
    then $\int_a^{+\infty} f(x)\,dx = \lim_{t \to +\infty} \int_a^t f(x)\,dx = M$ for some real number $M \leqslant L$.

- **P-integrals**

  - $\int_0^{+\infty} \frac{1}{x^p}\, dx = \begin{cases} \frac{1}{p-1} & \text{if } p > 1 \\ +\infty & \text{if } p \leqslant 1 \end{cases}$

  - $\int_0^1 \frac{1}{x^p}\, dx = \begin{cases} \frac{1}{1-p} & \text{if } p < 1 \\ +\infty & \text{if } p \geqslant 1 \end{cases}$

  - $\int_a^{+\infty} \frac{1}{x^p}\, dx = \begin{cases} \frac{a^{1-p}}{p-1} & \text{if } p > 1 \\ +\infty & \text{if } p \leqslant 1 \end{cases}$

  - $\int_0^a \frac{1}{x^p}\, dx = \begin{cases} \frac{a^{1-p}}{1-p} & \text{if } p < 1 \\ +\infty & \text{if } p \geqslant 1 \end{cases}$

- **Bypass L'Hospital's Rule**

  $$\ln\left(\ln\left(x\right)\right),\ \ln\left(x\right),\ \cdots\ x^{\frac{1}{100}},\ x^{\frac{1}{3}},\ \sqrt{x},\ 1,\ x^2,\ x^3,\ \cdots\ e^x,\ e^{2x},\ e^{3x},\ \cdots,\ e^{x^2},\ \cdots\ e^{e^x}.$$

  Essentially what it means is things on the right grow faster than things on the left. Thus, if we have say:

  $$\lim_{x\to\infty} \frac{x^2}{e^{2x}}.$$

  We can be sure that it is zero. Because this is $x^2 \cdot e^{-2x}$. If we take $\lim\limits_{x\to\infty} x^2 e^{-2x}$, we get $\infty \cdot 0$. As we see by the sequence e^{-2x} overrules x^2 and we can say the limit is zero.

- **Consideration for Limits**: Let $f : A \to B$ be a function defined by $x \mapsto f(x)$. If a point c lies outside the domain A, then the expression $\lim\limits_{x\to c} f(x)$ is not meaningful, and we classify this limit as undefined. For instance, the function arcsine has a domain of $[-1, 1]$. Therefore, limits like $\lim\limits_{x\to a} \sin^{-1}(x)$ where $a \notin [-1, 1]$ are undefined.

- **Why does**

  $$\lim_{x\to 2} \tan^{-1} \frac{1}{x-2}.$$

  $$= \lim_{x\to 2^-} \tan^{-1} \frac{1}{x-2} \qquad\qquad = \lim_{x\to 2^+} \tan^{-1} \frac{1}{x-2}$$
  $$= \lim_{x\to -\infty} \tan^{-1} x \qquad\qquad\qquad = \lim_{x\to +\infty} \tan^{-1} x$$
  $$= -\pi/2. \qquad\qquad\qquad\qquad = \frac{\pi}{2}.$$

1.4 Chapter 5 Definitions and Theorems

- **Sequence notation**

$$\{a_n\}_{n=1}^{\infty}, \text{ or simply } \{a_n\}.$$

- **Sequence notation (ordered list)**

$$a_1, \ a_2, \ a_3, \ \cdots, \ a_n, \ \cdots.$$

- **Arithemetic Sequence Difference**

$$d = a_n - a_{n-1}.$$

- **Arithmetic sequence (common difference between subsequent terms) general form**

$$\text{Index starting at } 0: \ a_n = a + nd$$
$$\text{Index starting at } 1: \ a_n = a + (n-1)d$$

.

- **Arithmetic sequence (common difference between subsequent terms) recursive form**

$$a_n = a_{n-1} + d.$$

- **Sum of arithmetic sequence**

$$S_n = \frac{n}{2}\left[a + a_n\right]$$
$$S_n = \frac{n}{2}\left[2a + (n-1)d\right].$$

- **Geometric sequence form common ratio**

$$r = \frac{a_n}{a_{n-1}}.$$

- **Geometric sequence general form**

$$a_n = ar^n \ (\text{Index starting at } 0)$$
$$a_n = a^{n+1}(\text{index starting at 0 and a=r})$$
$$a_n = ar^{n-1} \ (\text{Index starting at } 1)$$
$$a_n = a^n(\text{index starting at 1 and a=r}).$$

- **Geometric sequence recursive form**

$$a_n = ra_{n-1}.$$

- **Sum of geometric sequence (finite terms)**

$$S_n = \frac{a(1 - r^n)}{1 - r} \quad r \neq 1.$$

- **Convergence / Divergence**: If

$$\lim_{n \to +\infty} a_n = L.$$

  We say that the sequence converges, else it diverges

- **Formal definition of limit of sequence**

$$\lim_{n \to +\infty} a_n = L \iff \forall \varepsilon > 0, \exists N \in \mathbb{Z} \mid |a_n - L| < \varepsilon, \text{ if } n \geqslant n.$$

  Then we can say

$$\lim_{n \to +\infty} a_n = L \text{ or } a_n \to L.$$

- **Limit of a sequence defined by a function**: Consider a sequence $\{a_n\}$ such that $a_n = f(n)$ for all $n \geqslant 1$. If there exists a real number L such that

$$\lim_{x \to \infty} f(x) = L,$$

  then $\{a_n\}$ converges and

$$\lim_{n \to \infty} a_n = L.$$

- **Algebraic limit laws**: Given sequences $\{a_n\}$ and $\{b_n\}$ and any real number c, if there exist constants A and B such that $\lim_{n \to \infty} a_n = A$ and $\lim_{n \to \infty} b_n = B$, then

  - $\lim_{n \to \infty} c = c$
  - $\lim_{n \to \infty} ca_n = c \lim_{n \to \infty} a_n = cA$
  - $\lim_{n \to \infty} (a_n \pm b_n) = \lim_{n \to \infty} a_n \pm \lim_{n \to \infty} b_n = A \pm B$
  - $\lim_{n \to \infty} (a_n \cdot b_n) = (\lim_{n \to \infty} a_n) \cdot (\lim_{n \to \infty} b_n) = A \cdot B$
  - $\lim_{n \to \infty} \frac{a_n}{b_n} = \frac{\lim_{n \to \infty} a_n}{\lim_{n \to \infty} b_n} = \frac{A}{B}$, provided $B \neq 0$ and each $b_n \neq 0$.

- **Continuous Functions Defined on Convergent Sequences**: Consider a sequence $\{a_n\}$ and suppose there exists a real number L such that the sequence $\{a_n\}$ converges to L. Suppose f is a continuous function at L. Then there exists an integer N such that f is defined at all values a_n for $n \geqslant N$, and the sequence $\{f(a_n)\}$ converges to $f(L)$.

- **Squeeze Theorem for Sequences**: Consider sequences $\{a_n\}$, $\{b_n\}$, and $\{c_n\}$. Suppose there exists an integer N such that

$$a_n \leqslant b_n \leqslant c_n \text{ for all } n \geqslant N.$$

  If there exists a real number L such that

$$\lim_{n \to \infty} a_n = L = \lim_{n \to \infty} c_n,$$

  then $\{b_n\}$ converges and $\lim_{n \to \infty} b_n = L$

- **Bounded above**: A sequence $\{a_n\}$ is bounded above if there exists a real number M such that

$$a_n \leqslant M$$

  for all positive integers n.

- **Bounded below**: A sequence $\{a_n\}$ is bounded below if there exists a real number M such that

$$M \leqslant a_n$$

  for all positive integers n.

- **Bounded**: A sequence $\{a_n\}$ is a bounded sequence if it is bounded above and bounded below.

- **Unbounded**: If a sequence is not bounded, it is an unbounded sequence.

- **If a sequence $\{a_n\}$ converges, then it is bounded.**

- **Increasing sequence**: A sequence $\{a_n\}$ is increasing for all $n \geqslant n_0$ if

$$a_n \leqslant a_{n+1} \text{ for all } n \geqslant n_0.$$

- **Decreasing sequence**: A sequence $\{a_n\}$ is decreasing for all $n \geqslant n_0$ if

$$a_n \geqslant a_{n+1} \text{ for all } n \geqslant n_0.$$

- **Monotone sequence**: A sequence $\{a_n\}$ is a **monotone sequence** for all $n \geqslant n_0$ if it is increasing for all $n \geqslant n_0$ or decreasing for all $n \geqslant n_0$

- **Monotone Convergence Theorem**: If $\{a_n\}$ is a bounded sequence and there exists a positive integer n_0 such that $\{a_n\}$ is monotone for all $n \geqslant n_0$, then $\{a_n\}$ converges.

- **Infinite Series form:**

$$\sum_{n=1}^{\infty} a_n = a_1 + a_2 + a_3 + \cdots ..$$

- **Partial sum (k^{th} partial sum)**

$$S_k = \sum_{n=1}^{k} a_n = a_1 + a_2 + a_3 + \cdots + a_k.$$

- **Convergence of infinity series notation**

For a series, say...

$$\sum_{n=1}^{\infty} a_n \ .$$

its convergence is determined by the limit of its sequence of partial sums. Specifically, if

$$\lim_{n \to +\infty} S_n = S \to \sum_{n=1}^{\infty} a_n \ = S.$$

- **Harmonic series**

$$\sum_{n=1}^{\infty} \frac{1}{n} = \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \dots \ .$$

Which diverges to $+\infty$

- **Algebraic Properties of Convergent Series** Let $\sum_{n=1}^{\infty} a_n$ and $\sum_{n=1}^{\infty} b_n$ be convergent series. Then the following algebraic properties hold:

  1. The series $\sum_{n=1}^{\infty}(a_n + b_n)$ converges and

$$\sum_{n=1}^{\infty}(a_n + b_n) = \sum_{n=1}^{\infty} a_n + \sum_{n=1}^{\infty} b_n. \quad \text{(Sum Rule)}.$$

2. The series $\sum_{n=1}^{\infty}(a_n - b_n)$ converges and

$$\sum_{n=1}^{\infty}(a_n - b_n) = \sum_{n=1}^{\infty} a_n - \sum_{n=1}^{\infty} b_n. \quad \text{(Difference Rule)}.$$

3. For any real number c, the series $\sum_{n=1}^{\infty} ca_n$ converges and

$$\sum_{n=1}^{\infty} ca_n = c\sum_{n=1}^{\infty} a_n. \quad \text{(Constant Multiple Rule)}.$$

- **Geometric series convergence or divergence:**

$$\sum_{n=1}^{\infty} ar^{n-1} = \begin{cases} \frac{a}{1-r} & \text{if } |r| < 1 \\ diverges & \text{if } |r| \geqslant 1 \end{cases}.$$

- **Divergence test**: In the context of sequences, if $\lim_{n\to\infty} a_n = c \neq 0$ or the limit does not exist, then the series $\sum_{n=1}^{\infty} a_n$ is said to diverge. The converse is not true.

  Because:

$$\lim_{k\to\infty} a_k = \lim_{k\to\infty}(S_k - S_{k-1}) = \lim_{k\to\infty} S_k - \lim_{k\to\infty} S_{k-1} = S - S = 0..$$

- **Integral Test Prelude**: for any integer k, the kth partial sum S_k satisfies

$$S_k = a_1 + a_2 + a_3 + \cdots + a_k < a_1 + \int_1^k f(x)\,dx < a_1 + \int_1^{\infty} f(x)\,dx..$$

  and

$$S_k = a_1 + a_2 + a_3 + \cdots + a_k > \int_1^{k+1} f(x)\,dx..$$

- **Intgeral test** Suppose $\sum_{n=1}^{\infty} a_n$ is a series with positive terms a_n Suppose there exists a function f and a positive integer N such that the following three conditions are satisfied:

  1. f positive, continuous, and decreasing on $[N, \infty)$
  2. $f(n) = a_n$ for all integers $n \geqslant N$, $N \in \mathbb{Z}^+$

Then the series $\sum_{n=1}^{\infty} a_n$ and the improper integral $\int_N^{\infty} f(x)\,dx$ either both converge or both diverge..

- **P-series** $\forall p \in \mathbb{R}$, the series

$$\sum_{n=1}^{\infty} \frac{1}{n^P}.$$

Is called a **p-series**. Furthermore,

$$\sum_{n=1}^{\infty} \frac{1}{n^p} \begin{cases} \text{converges if } p > 1 \\ \text{diverges if } p \leqslant 1. \end{cases}.$$

- **P-series extended**

$$\sum_{n=2}^{\infty} \frac{1}{n \ln (n)^p} \begin{cases} \text{converges if } p > 1 \\ \text{diverges if } p \leqslant 1. \end{cases}$$

- **Remainder estimate for the integral test** Suppose $\sum_{n=1}^{\infty} a_n$ is a convergent series with positive terms. Suppose there exists a function f and a positive integer M satisfying the following three conditions:

  1. f is positive, decreasing, and continuous on $[M, \infty)$
  2. $f(n) = a_n$ for all integers $n \geqslant M$.

  Let S_N be the Nth partial sum of $\sum_{n=1}^{\infty} a_n$. For all positive integers N,

  $$S_N + \int_{N+1}^{\infty} f(x) \, dx < \sum_{n=1}^{\infty} a_n < S_N + \int_{N}^{\infty} f(x) \, dx.$$

  In other words, the remainder $R_N = \sum_{n=1}^{\infty} a_n - S_N = \sum_{n=N+1}^{\infty} a_n$ satisfies the following estimate:

  $$\int_{N+1}^{\infty} f(x) \, dx < R_N < \int_{N}^{\infty} f(x) \, dx.$$

  This is known as the remainder estimate

  To find a value of N such that we are withing a desired margin of error, Since we know $R_n < \int_{N}^{\infty} f(x) \, dx$. Simply compute the improper integral and set the result $<$ the desired error to solve for N

- **Find a_n given the expression for the partial sum**

  $$a_n = S_n - S_{n-1}.$$

- **telescoping series**: Telescoping series are a type of series where each term cancels out a part of another term, leaving only a few terms that do not cancel. When you sum the series, most of the terms collapse or "telescope," which simplifies the calculation of the sum. Here are some key points and generalizations you can note about telescoping series:

  - Partial Fraction Decomposition
  - Cancellation Pattern: In a telescoping series, look for a pattern where a term in one fraction will cancel out with a term in another fraction.
  - Write out Terms
  - What is left is S_n, thus the sum of the series is the $\lim_{n \to \infty} S_n$

  Try:

  $$\sum_{n=2}^{\infty} \frac{1}{n^2 - 1}.$$

  Hint, its not only the first and last terms cancel, we also have a $\frac{1}{n}^{\frac{1}{2}}$, when a_{n-1}: Answer is $\frac{3}{4}$

- **Comparison test for series**

    1. Suppose there exists an integer N such that $0 \leqslant a_n \leqslant b_n$ for all $n \geqslant N$. If $\sum_{n=1}^{\infty} b_n$ converges, then $\sum_{n=1}^{\infty} a_n$ converges.
    2. Suppose there exists an integer N such that $a_n \geqslant b_n \geqslant 0$ for all $n \geqslant N$. If $\sum_{n=1}^{\infty} b_n$ diverges, then $\sum_{n=1}^{\infty} a_n$ diverges.

- **Limit Comparison Test** Let $a_n, b_n \geqslant 0$ for all $n \geqslant 1$.

    - If $\lim_{n \to \infty} \frac{a_n}{b_n} = L \neq 0$, then $\sum_{n=1}^{\infty} a_n$ and $\sum_{n=1}^{\infty} b_n$ both converge or both diverge.

    - If $\lim_{n \to \infty} \frac{a_n}{b_n} = 0$ and $\sum_{n=1}^{\infty} b_n$ converges, then $\sum_{n=1}^{\infty} a_n$ converges.

    - If $\lim_{n \to \infty} \frac{a_n}{b_n} = \infty$ and $\sum_{n=1}^{\infty} b_n$ diverges, then $\sum_{n=1}^{\infty} a_n$ diverges.

Note: Note that if $\frac{a_n}{b_n} \to 0$ and $\sum_{n=1}^{\infty} b_n$ diverges, the limit comparison test gives no information. Similarly, if $\frac{a_n}{b_n} \to \infty$ and $\sum_{n=1}^{\infty} b_n$ converges, the test also provides no information.

Consider the series

$$\sum_{n=1}^{\infty} \frac{n^4 + 6}{n^5 + 4}.$$

To find our b_n we can only focus on the leading coefficients. Thus:

$$b_n = \frac{n^4}{n^5} = \frac{1}{n}.$$

So our test...

$$\lim_{n \to \infty} \frac{a_n}{b_n} = \frac{\frac{n^4 + 6}{n^5 + 4}}{\frac{1}{n}}$$

$$= \lim_{n \to \infty} \frac{n(n^4 + 6)}{n^5 + 4}$$

$$= \lim_{n \to \infty} \frac{n^5 + 6n}{n^5 + 4}$$

$$= 1.$$

Since $\lim\limits_{n \to \infty} \frac{a_n}{b_n} \neq 0 \vee +\infty$. And $\frac{1}{n}$ diverges, we can conclude that a_n will also diverge.

- **Determine which series (or function) is greater**

    - **Subtraction**: Given two functions $f(x) = \frac{1}{x}$ and $g(x) = \frac{x^4 + 6}{x^5 + 4}$, we want to compare them by considering the function $h(x) = f(x) - g(x)$:

$$h(x) = f(x) - g(x) = \frac{1}{x} - \frac{x^4 + 6}{x^5 + 4}$$

To compare these directly, it would be helpful to have a common denominator:

$$h(x) = \frac{x^4 + 4 - (x^4 + 6)}{x(x^5 + 4)} = \frac{-2}{x(x^5 + 4)}$$

Now, we can see that the sign of $h(x)$ depends on the sign of x because the denominator $x(x^5 + 4)$ is always positive for $x \neq 0$. So:

∗ For $x > 0$, $h(x) < 0$, which means $f(x) < g(x)$.

∗ For $x < 0$, $h(x) > 0$, which means $f(x) > g(x)$.

- **Alternating Series** Any series whose terms alternate between positive and negative values is called an alternating series. An alternating series can be written in the form

$$\sum_{n=1}^{\infty} (-1)^{n+1} b_n = b_1 - b_2 + b_3 - b_4 + \cdots .$$

or

$$\sum_{n=1}^{\infty} (-1)^n b_n = -b_1 + b_2 - b_3 + b_4 - \cdots .$$

Where $b_n > 0$ for all positive integers n.

- **alternating series test (Leibniz criterion)** An alternating series of the form

$$\sum_{n=1}^{\infty} (-1)^{n+1} b_n \quad \text{or} \quad \sum_{n=1}^{\infty} (-1)^n b_n$$

converges if

– $0 < b_{n+1} \leqslant b_n \ \forall \ n \geqslant 1$

– $\lim_{n \to \infty} b_n = 0$.

Note: We remark that this theorem is true more generally as long as there exists some integer N such that $0 < b_{n+1} \leqslant b_n$ for all $n \geqslant N$.

Additional note: The AST allows us to consider just the positive terms to check for these two conditions because if a series of decreasing positive terms that approach zero is alternated in sign, the alternating series will converge. This is a special property of alternating series that does not generally hold for non-alternating series.

- **Show decreasing (For the AST)**: Consider the series

$$\sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^2} .$$

So you see we have $b_n = \frac{1}{n^2}$. For the AST, we must show that this is decreasing. If $b_{n+1} = \frac{1}{(n+1)^2}$. Then we see

$$\frac{1}{(n+1)^2} < \frac{1}{n^2}.$$

Thus it is decreasing for $n \geqslant 1$ $(b_{n+1} < b_n)$ ∎

- **Remainders in alternating series** Consider an alternating series of the form

$$\sum_{n=1}^{\infty} (-1)^{n+1} b_n \quad \text{or} \quad \sum_{n=1}^{\infty} (-1)^n b_n,$$

that satisfies the hypotheses of the alternating series test. Let S denote the sum of the series and S_N denote the N-th partial sum. For any integer $N \geqslant 1$, the remainder $R_N = S - S_N$ satisfies

$$|R_N| \leqslant b_{N+1}.$$

This tells us that if we stop at the Nth term, the error we are making is at most the size of the next term

- **Absolute and conditional convergence**

    - A series $\sum_{n=1}^{\infty} a_n$ exhibits absolute convergence if $\sum_{n=1}^{\infty} |a_n|$ converges.
    - A series $\sum_{n=1}^{\infty} a_n$ exhibits conditional convergence if $\sum_{n=1}^{\infty} a_n$ converges but $\sum_{n=1}^{\infty} |a_n|$ diverges.
    - If $\sum_{n=1}^{\infty} |a_n|$ converges then $\sum_{n=1}^{\infty} a_n$ converges

  Note: if $|a_n|$ diverges, we cannot have absolute convergence, thus we must examine to see if normal a_n converges, in which case we would have conditional convergence

  Big Note: If a series not strictly decreasing, we can still check for absolute/conditional convergence. Take $\sum_{n=1}^{\infty} \frac{\sin n}{3^n + 4}$ for example.

- **Ratio test** Let $\sum_{n=1}^{\infty} a_n$ be a series with nonzero terms. Let

$$\rho = \lim_{n \to \infty} \left| \frac{a_{n+1}}{a_n} \right|..$$

  Then:

    i. If $0 \leqslant \rho < 1$, then $\sum_{n=1}^{\infty} a_n$ converges absolutely.
    ii. If $\rho > 1$ or $\rho = \infty$, then $\sum_{n=1}^{\infty} a_n$ diverges.
    iii. If $\rho = 1$, the test does not provide any information.

  Note: The ratio test is useful for series whose terms involve factorials

- **Root test** Consider the series $\sum_{n=1}^{\infty} a_n$. Let

$$\rho = \lim_{n \to \infty} \sqrt[n]{|a_n|}..$$

    i. If $0 \leqslant \rho < 1$, then $\sum_{n=1}^{\infty} a_n$ converges absolutely.
    ii. If $\rho > 1$ or $\rho = \infty$, then $\sum_{n=1}^{\infty} a_n$ diverges.
    iii. If $\rho = 1$, the test does not provide any information.

  Note: The root test is useful for series whose terms involve exponentials

- **Which tests require positive terms**

    - The **Integral Test:** This test applies to series where the terms come from a function that is positive, continuous, and decreasing on a certain interval. The convergence or divergence of the series is determined by the convergence or divergence of the corresponding improper integral of the function.
    - The **Remainder estimate for the integral test**
    - The **Comparison Test:** This test compares the terms of a series to those of another series with known convergence behavior. It requires that the terms of both series be positive or non-negative.
    - The **Limit Comparison Test:** Similar to the Comparison Test, this test involves comparing the terms of two series by taking the limit of the ratio of their terms. It requires that the terms of both series be positive.
    - In **alternating series**, b_n must have only positive terms

1.5   Chapter 6 Definitions and Theorems

- **Euler definition for** e

$$e^a = \lim_{n\to\infty} \left(1 + \frac{a}{n}\right)^n$$

$$\frac{1}{e^a} = \lim_{n\to\infty} \left(1 + \frac{-a}{n}\right)^n$$

$$\frac{1}{e^a} = \lim_{n\to\infty} \left(\frac{n}{n+a}\right)^n.$$

- **Other definition for** e

$$e = \sum_{n=0}^{\infty} \frac{1}{n!}$$

$$e - 1 = \sum_{n=1}^{\infty} \frac{1}{n!}$$

$$e^x = \sum_{n=0}^{\infty} \frac{x^n}{n!}.$$

- **Power series**: A series of the form

$$\sum_{n=0}^{\infty} c_n x^n = c_0 + c_1 x + c_2 x^2 + \cdots.$$

is a power series centered at $x = 0$.

A series of the form

$$\sum_{n=0}^{\infty} c_n (x-a)^n = c_0 + c_1(x-a) + c_2(x-a)^2 + \cdots.$$

is a power series centered at $x = a$.

- **Convergence of a Power Series**

Consider the power series $\sum_{n=0}^{\infty} c_n (x-a)^n$. The series satisfies exactly one of the following properties:

 (i) The series converges at $x = a$ and diverges for all $x \neq a$.

 (ii) The series converges for all real numbers x.

 (iii) There exists a real number $R > 0$ such that the series converges if $|x - a| < R$ and diverges if $|x - a| > R$. At the values x where $|x - a| = R$, the series may converge or diverge.

- **A power series always converges at its center**

- **Radius of convergence**: Consider the power series $\sum_{n=0}^{\infty} c_n (x-a)^n$. The set of real numbers x where the series converges is the interval of convergence. If there exists a real number $R > 0$ such that the series converges for $|x - a| < R$ and diverges for $|x - a| > R$, then R is the radius of convergence. If the series converges only at $x = a$, we say the radius of convergence is $R = 0$. If the series converges for all real numbers x, we say the radius of convergence is $R = \infty$ (Figure 6.2).

- **Finding interval of convergence and radius of convergence**

  - Fact: power series is always convergent on its center
  - Use ratio test (values of ρ)
  - Use $\rho < 1$ to find Radius of convergence
  - Test end points of interval by plugging into original series and seeing whether the series is convergent or divergent

- **If $\rho = 0$, the power series converges for all x**

- **If $\rho = \infty$, the series diverges for all $x \neq a$**

- **Combining Power Series:** Suppose that the two power series $\sum_{n=0}^{\infty} c_n x^n$ and $\sum_{n=0}^{\infty} d_n x^n$ converge to the functions f and g, respectively, on a common interval I.

  (i) The power series $\sum_{n=0}^{\infty} (c_n x^n \pm d_n x^n)$ converges to $f \pm g$ on I.

  (ii) For any integer $m \geqslant 0$ and any real number b, the power series $\sum_{n=0}^{\infty} b x^m c_n x^n$ converges to $b x^m f(x)$ on I.

  Eg: If we know $\sum_{n=0}^{\infty} a_n x_n$ has $I = (-1, 1)$. Then

  $$\sum_{n=0}^{\infty} a_n 3^n x^n$$
  $$= \sum_{n=0}^{\infty} a_n (3x)^n$$
  $$I = (-3, 3).$$

  (iii) For any integer $m \geqslant 0$ and any real number b, the series $\sum_{n=0}^{\infty} c_n (b x^m)^n$ converges to $f(b x^m)$ for all x such that $b x^m$ is in I.

- **For part I, II, and III, the interval of the combined series is the smaller interval**

- **Cauchy product (Multiplying power series):** Suppose that the power series $\sum_{n=0}^{\infty} c_n x^n$ and $\sum_{n=0}^{\infty} d_n x^n$ converge to f and g, respectively, on a common interval I. Let

  $$e_n = c_0 d_n + c_1 d_{n-1} + c_2 d_{n-2} + \cdots + c_{n-1} d_1 + c_n d_0$$
  $$= \sum_{k=0}^{n} c_k d_{n-k}..$$

  Then

  $$\left(\sum_{n=0}^{\infty} c_n x^n \right) \left(\sum_{n=0}^{\infty} d_n x^n \right) = \sum_{n=0}^{\infty} e_n x^n$$

  and

  $$\sum_{n=0}^{\infty} e_n x^n \text{ converges to } f(x) \cdot g(x) \text{ on } I.$$

  The series $\sum_{n=0}^{\infty} e_n x^n$ is known as the Cauchy product of the series $\sum_{n=0}^{\infty} c_n x^n$ and $\sum_{n=0}^{\infty} d_n x^n$.

- **Sterling's Approximation**

$$n! \approx \sqrt{2\pi n} \left(\frac{n}{e}\right)^n.$$

- **Gamma function (extension of the factorial function)**

$$\Gamma(z) = \int_0^\infty e^{-t} t^{z-1} \, dt$$

Thus, $n! = \Gamma(n+1)$.

- **Cool definition for** e^x

$$f'(x) = rf(x)$$
$$\implies f(x) = ce^{rx}.$$

- **Term-by-Term Differentiation and Integration for Power Series.** Suppose that the power series $\sum_{n=0}^\infty c_n(x-a)^n$ converges on the interval $(a-R, a+R)$ for some $R > 0$. Let f be the function defined by the series

$$f(x) = \sum_{n=0}^\infty c_n(x-a)^n = c_0 + c_1(x-a) + c_2(x-a)^2 + c_3(x-a)^3 + \cdots$$

for $|x-a| < R$. Then f is differentiable on the interval $(a-R, a+R)$ and we can find f' by differentiating the series term-by-term:

$$f'(x) = \sum_{n=1}^\infty nc_n(x-a)^{n-1} = c_1 + 2c_2(x-a) + 3c_3(x-a)^2 + \cdots$$

for $|x-a| < R$. Also, to find $\int f(x)\,dx$, we can integrate the series term-by-term. The resulting series converges on $(a-R, a+R)$, and we have

$$\int f(x)\,dx = C + \sum_{n=0}^\infty \frac{c_n(x-a)^{n+1}}{n+1} = C + c_0(x-a) + \frac{c_1(x-a)^2}{2} + \frac{c_2(x-a)^3}{3} + \cdots$$

for $|x-a| < R$.

NOTE! when a power series is differentiated or integrated term-by-term, it says nothing about what happens at the endpoints.

- **Uniqueness of Power Series**: Let $\sum_{n=0}^\infty c_n(x-a)^n$ and $\sum_{n=0}^\infty d_n(x-a)^n$ be two convergent power series such that

$$\sum_{n=0}^\infty c_n(x-a)^n = \sum_{n=0}^\infty d_n(x-a)^n$$

for all x in an open interval containing a. Then $c_n = d_n$ for all $n \geqslant 0$.

- **When finding the Cauchy product of two power series, we include the zero term when finding the new power series general term. For integrating and differentiating, we do not**

- **Taylor and Maclaurin series**: If f has derivatives of all orders at $x = a$, then the Taylor series for the function f at a is

$$\sum_{n=0}^\infty \frac{f^{(n)}(a)}{n!}(x-a)^n = f(a) + f'(a)(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \cdots + \frac{f^{(n)}(a)}{n!}(x-a)^n + \cdots.$$

$$(16)$$

The Taylor series for f at 0 is known as the Maclaurin series for f.

- **Uniqueness of Taylor series**: If a function f has a power series at a that converges to f on some open interval containing a, then that power series is the Taylor series for f at a.

- **Taylor-Macluarin Polynomials**: If f has n derivatives at $x = a$, then the nth Taylor polynomial for f at a is

$$p_n(x) = f(a) + f'(a)(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \frac{f'''(a)}{3!}(x-a)^3 + \cdots + \frac{f^{(n)}(a)}{n!}(x-a)^n. \quad (17)$$

The nth Taylor polynomial for f at 0 is known as the nth Maclaurin polynomial for f.

- **Taylor's Theorem with Remainder**: Let f be a function that can be differentiated $n+1$ times on an interval I containing the real number a. Let p_n be the nth Taylor polynomial of f at a and let

$$R_n(x) = f(x) - p_n(x)$$

be the nth remainder. Then for each x in the interval I, there exists a real number c between a and x such that

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

If there exists a real number M such that $\left|f^{(n+1)}(x)\right| \leqslant M$ for all $x \in I$, then

$$|R_n(x)| \leqslant \frac{M}{(n+1)!}\, |x-a|^{n+1}$$

$\forall\ x \in I$

- **Maclaurin Series/Polynomials for sine**: The Taylor series for the sine function is

$$\sin(x) = \sum_{n=0}^{\infty} (-1)^n \frac{x^{2n+1}}{(2n+1)!} \ = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \dots \quad \text{For } x \in \mathbb{R}.$$

Where p_n obeys

$$p_{2m+1} = p_{2m+2}$$
$$= x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \dots + \frac{(-1)^m x^{2m+1}}{(2m+1)!}.$$

Note: When discussing specific polynomials, say P_5 for example, we arnt talking about the first 5 terms in the series above, we are talking about the polynomial `up to` degree 5. Thus it would have 3 terms

- **Maclaurin Series/Polynomials for cosine**: Similar to the sine function, the Maclaurin series for the cosine function is

$$\cos(x) = \sum_{n=0}^{\infty} (-1)^n \frac{x^{2n}}{(2n)!} \ = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \dots \quad \text{For } x \in \mathbb{R}.$$

Where p_n obeys

$$p_{2m} = p_{2m+1}$$
$$= 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \dots + (-1)^n \frac{x^{2m}}{(2m)!}.$$

- **Maclaurin Series/Polynomials for e^x**: We find the Maclaurin series for the exponential function to be

$$e^x = \sum_{n=0}^{\infty} \frac{x^n}{n!} \ = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots \quad \text{For } x \in \mathbb{R}.$$

Note: this definition is described above but now we have a way of showing its truthiness

- **Convergence of Taylor Series**: Suppose that f has derivatives of all orders on an interval I containing a. Then the Taylor series

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

converges to $f(x)$ for all x in I if and only if

$$\lim_{n \to \infty} R_n(x) = 0$$

for all x in I.

Note: With this theorem, we can prove that a Taylor series for f at a converges to f if we can prove that the remainder $R_n(x) \to 0$. To prove that $R_n(x) \to 0$, we typically use the bound

$$|R_n(x)| \leqslant \frac{M}{(n+1)!}|x-a|^{n+1}$$

from Taylor's theorem with remainder.

- **Using taylor series to find limits**: Consider the limit $\lim\limits_{x \to 0+} \frac{\cos \sqrt{x}-1}{2x}$. We know we have a problem if we attempt to use the `direct substitution property`. Thus, we can substitute $\cos(\sqrt{x})$ for its `Maclaurin series` and see what happens. We know the maclaurin series for $\cos(x)$ is

$$\cos x \sim \sum_{n=0}^{\infty} (-1)^n \frac{x^{2n}}{(2n)!} \quad = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \dots$$

$$\implies \cos \sqrt{x} \sim \sum_{n=0}^{\infty} (-1)^n \frac{(x^{\frac{1}{2}})^{2n}}{(2n)!} \quad = 1 - \frac{(x^{\frac{1}{2}})^2}{2!} + \frac{(x^{\frac{1}{2}})^4}{4!} - \frac{(x^{\frac{1}{2}})^6}{6!} + \dots$$

$$= \sum_{n=0}^{\infty} (-1)^n \frac{x^n}{(2n)!} \quad = 1 - \frac{x}{2!} + \frac{x^2}{4!} - \frac{x^3}{6!} + \dots.$$

So we have

$$\lim_{x \to 0^+} \frac{\left(1 - \frac{x}{2!} + \frac{x^2}{4!} - \frac{x^3}{6!} + \dots\right) - 1}{2x}$$

$$= \lim_{x \to 0^+} \frac{\left(-\frac{x}{2!} + \frac{x^2}{4!} - \frac{x^3}{6!} + \dots\right)}{2x}$$

$$= \lim_{x \to 0^+} \left(-\frac{x}{2!} + \frac{x^2}{4!} - \frac{x^3}{6!} + \dots\right) \cdot \frac{1}{2x}$$

$$= \lim_{x \to 0^+} -\frac{1}{4}$$

$$= -\frac{1}{4}.$$

- **Multiplying a known Taylor series by some other function:** Consider $f(x) = x\cos x$. Since we know that the taylor series for $\cos(x) = \sum\limits_{n=0}^{\infty} (-1)^n \frac{x^{2n}}{(2n)!}$, which converges $\forall\ x \in \mathbb{R}$. We can easily just multiply this by x to get the taylor series for $f(x) = x\cos(x)$. Since the Taylor series for $\cos(x)$ converges for all real x, multiplying it by x won't affect its convergence properties. The resulting series will still converge for all x.

Note: The product of the Taylor series and the function will be valid only where both the series converges and the function is well-defined. Probably analyze the convergence of the product series.

- **Multiplying a known Taylor series by some other function where convergence is affected:** Consider the example above. Although this time suppose we multiply $\cos(x)$ by $\frac{1}{x}$ instead of x. We know the resulting taylor series must not be convergent at $x = 0$ because $\frac{1}{x}$ is not defined at zero. It is important to understand that we will not get this conclusion from the ratio test alone. The Ratio Test alone does not account for points where the series or its terms are not defined.

  TLDR: Be mindful about the domain of the function you are multiplying the Taylor series by. Do not only rely on the ratio test to find points of convergence.

- **Analytic function:**
  - An analytic function is infinitely differentiable within its domain.
  - An analytic function can be represented by a convergent power series (like a Taylor series) around any point in its domain.
  - The power series representing an analytic function not only exists but also converges to the function within a certain radius around the point of expansion

- **Maclaurin series for $\frac{1}{1-x}$:**

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

- **Maclaurin series for $\ln(1+x)$:**

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

- **Maclaurin series for $\tan^{-1} x$:**

$$\tan^{-1} x \sim \sum_{n=0}^{\infty} (-1)^n \frac{x^{2n+1}}{2n+1} \quad \text{for } |x| \leqslant 1.$$

- **Binomial expansion for $(1+x)^r$ for $r \in \mathbb{Z}^+$**

$$(1+x)^r = \sum_{n=0}^{r} \binom{r}{n} x^n \quad r \in \mathbb{Z}^+.$$

- **Binomial expansion for $(1+x)^r$ for $r \in \mathbb{R}$**

$$(1+x)^r = \sum_{n=0}^{\infty} \binom{r}{n} x^n = 1 + rx + \frac{r(r-1)}{2!} x^2 + \cdots + \frac{r(r-1)\cdots(r-n+1)}{n!} x^n + \cdots.$$

Where

$$\binom{r}{n} = \frac{f^{(n)}(0)}{n!} = \frac{r(r-1)(r-2)\cdot...\cdot(r-n+1)}{n!}.$$

Note: When $n = 0$, $\binom{r}{0} = 1$, when $n = 1$, $\binom{r}{1} = r$, when $n = 2$, $\binom{r}{2} = \frac{r(r-1)}{2!}$, etc...

- **The binomial theorem:** For any real number r, the Maclaurin series for $f(x) = (1+x)^r$ is the binomial series. It converges to f for $|x| < 1$, and we write

$$(1+x)^r = \sum_{n=0}^{\infty} \binom{r}{n} x^n = 1 + rx + \frac{r(r-1)}{2!} x^2 + \cdots + \frac{r(r-1)\cdots(r-n+1)}{n!} x^n + \cdots$$

for $|x| < 1$.

1.6   Chapter 6 Problems to Remember

- **Problem to remember (Properties of power series):** Evaluate the infinite series by identifying it as the value of an integral of a geometric series.

$$\sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \; .$$

Remark. If we can find which geometric power series's integral (with some bounds) gives us the given series, we can then integrate the function representation to get the value of the original series. Consider the geometric power series

$$\frac{1}{1+x^2} = \frac{1}{1-(-x^2)} = \sum_{n=0}^{\infty} (-x^2)^n = \sum_{n=0}^{\infty} (-1)^n x^{2n} \; .$$

Suppose we then integrate the power series

$$\int \sum_{n=0}^{\infty} (-1)^n x^{2n} \; dx$$

$$= \sum_{n=0}^{\infty} (-1)^n \int x^{2n} \; dx$$

$$= \frac{1}{2n+1} x^{2n+1}.$$

Now we must deduce for which bounds will the FTC give us the original series $\sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1}$. We come to the conclusion

$$\sum_{n=0}^{\infty} (-1)^n \int_0^1 x^{2n} \; dx = \sum_{n} \frac{(-1)^n}{2n+1} \; .$$

This implies we can integrate the function representation of the geometric power series we just integrated to get the value of the infinite series $\sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1}$. Thus,

$$\int_0^1 \frac{1}{1+x^2} \; dx = \frac{\pi}{4}.$$

- **Problem to remember (Properties of power series):** Find the power series for $f(x) = \ln x$ centered at $x = 9$ by using term-by-term integration or differentiation.

Solution. The goal is to find a function that resembles one we know (sum of geometric series $\frac{a}{1-x}$) such that if we integrate or differentiate we can get $\ln x$. Since we know the integral of $\frac{1}{x}$ is $\ln x$, and we can easily manipulate $\frac{1}{x}$ to be in the form $\frac{a}{1-x}$, we choose $\frac{1}{x}$ to be the function to examine. Thus,

$$\frac{1}{x} = \frac{1}{9+x-9} = \frac{1}{9-(-(x-9))} = \frac{1/9}{1-\left(\frac{-(x-9)}{9}\right)}$$

$$\text{If } f(x) = \frac{a}{1-x} \sim \sum_{n=0}^{\infty} a(x^n) = a + ax + ax^2 + ax^3 + ...$$

$$\implies f(x) = \frac{1/9}{1-\left(\frac{-(x-9)}{9}\right)} \sim \sum_{n=0}^{\infty} \frac{1}{9} \left(\frac{-(x-9)}{9}\right)^n = \sum_{n=0}^{\infty} \frac{(-1)^n (x-9)^n}{9^{n+1}} \; .$$

Then we can throw in some integrals

$$\int f(x)\ dx = \int \frac{1/9}{1 - \left(\frac{-(x-9)}{9}\right)}\ dx = \int \sum_{n=0}^{\infty} \frac{(-1)^n(x-9)^n}{9^{n+1}}\ dx$$

$$\ln x = \sum_{n=0}^{\infty} \frac{(-1)^n}{9^{n+1}} \int (x-9)^n\ dx$$

$$\ln x = \sum_{n=0}^{\infty} \frac{(-1)^n(x-9)^{n+1}}{(n+1)9^{n+1}} + C.$$

If we let $x = 9$

$$\ln 9 = \sum_{n=0}^{\infty} \frac{(-1)^n(9-9)^{n+1}}{(n+1)9^{n+1}} + C$$

$$\ln 9 = C.$$

Thus, we have

$$f(x) = \ln 9 + \sum_{n=0}^{\infty} \frac{(-1)^n(9-9)^{n+1}}{(n+1)9^{n+1}}$$

.

Note: the "$+C$" is initially omitted from $\ln(x)$ because we're considering a specific antiderivative. When you integrate the power series, you include "$+C$" to account for the general form of the antiderivative. The value of C is then determined using a specific condition to match the specific antiderivative you're interested in.

- **Problem to remember**: Say we want to find the power series for $7x \ln 1 + x$. We can first find the power series for $\ln(1+x)$

$$\frac{d}{dx} \ln(1+x) = \frac{1}{1+x} = \frac{1}{1-(-x)}.$$

We know the power series for $\frac{1}{1-(-x)}$ is

$$\sum_{n=0}^{\infty} (-1)^n x^n$$

$$\implies \int \frac{1}{1+x} = \int \sum_{n=0}^{\infty} (-1)x^n$$

$$\ln(1+x) = \sum_{n=0}^{\infty} (-1)^n \frac{x^{n+1}}{n+1} + C$$

$$\ln(1+x) = \sum_{n=0}^{\infty} (-1)^n \frac{x^{n+1}}{n+1}.$$

Now that we have found the power series for $\ln(1+x)$, to find the power series for $7x \ln(1+x)$...

$$7x \sum_{n=0}^{\infty} (-1)^n \frac{x^{n+1}}{n+1}$$

$$\sum_{n=0}^{\infty} 7x \left((-1)^n \frac{x^{n+1}}{n+1}\right)$$

$$= \sum_{n=0}^{\infty} (-1)^n \frac{7x^{n+2}}{n+1}.$$

- **Problem to remember (Cumbersome taylor polynomial)**: Suppose we have some function f, and we would like to find the Taylor polynomial up to degree 3. Say $f(x) = e^{2x}\cos(x)$. We could find each derivative up to degree 3, however, given that we know the taylor series for both e^{2x} and $\cos(x)$.

$$e^{2x} = \sum_{n=0}^{\infty} \frac{(2x)^n}{n!} = 1 + 2x + \frac{4x^2}{2!} + \frac{8x^3}{3!} + \dots$$

$$\cos(x) = \sum_{n=0}^{\infty} (-1)^n \frac{x^{2n}}{(2n)!} = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} + \frac{x^6}{6!} + \dots \ .$$

We can find $P_3(x)$ by multiplying these Taylor series. Thus,

$$(1 + 2x + \frac{4x^2}{2!} + \frac{8x^3}{3!} + \dots)(1 - \frac{x^2}{2!} + \frac{x^4}{4!} + \frac{x^6}{6!} + \dots).$$

And we can find P_3 to be

$$P_3 = 1 + 2x + \frac{3}{2}x^2 + \frac{1}{3}x^3.$$

- **Problem to Remember (Using known Taylor series to find sum of series)**: Consider the series $\sum_{n=0}^{\infty} (-1)^n \frac{\left(\frac{1}{25}\right)^{n-3}}{2n+1}$

We notice this resembles the Taylor series for the arctangent function $\tan^{-1} x = \sum_{n=0}^{\infty} (-1)^n \frac{x^{2n+1}}{2n+1}$ for $|x| \leqslant 1$. Thus, we maipulate the series to better conform to the Taylor series for $\tan^{-1} x$.

$$\sum_{n=0}^{\infty} (-1)^n \frac{\left(\frac{1}{25}\right)^{n-3}}{2n+1}$$

$$= \sum_{n=0}^{\infty} (-1)^n \frac{\left(\frac{1}{5}\right)^{2n-6}}{2n+1}$$

$$= \sum_{n=0}^{\infty} (-1)^n \frac{\left(\frac{1}{5}\right)^{2n} 5^6}{2n+1}$$

$$= \sum_{n=0}^{\infty} (-1)^n \frac{\left(\frac{1}{5}\right)^{2n} 5^6 \left(\frac{1}{5}\right) 5}{2n+1}$$

$$= \sum_{n=0}^{\infty} (-1)^n \frac{\left(\frac{1}{5}\right)^{2n+1} 5^7}{2n+1}$$

.

Thus the sum will be

$$5^7 \tan^{-1} \frac{1}{5}.$$

Fundemental Physics: Classical Mechanics

2.1   Chapter 1: Units and Measurement

2.1.1   Key Terms

- **Physics**, which comes from the Greek *phúsis*, meaning "nature," is concerned with describing the interactions of energy, matter, space, and time to uncover the fundamental mechanisms that underlie every phenomenon.

- A **model** is a representation of something that is often too difficult (or impossible) to display directly. Although

- a **theory** is a testable explanation for patterns in nature supported by scientific evidence and verified multiple times by various groups of researchers.

- A **law** uses concise language to describe a generalized pattern in nature supported by scientific evidence and repeated experiments. Often, a law can be expressed in the form of a single mathematical equation.

- **SI units** (for the French Système International d'Unités), also known as the **metric system**.

- The Metric system may also be referred to as the **centimeter–gram–second (cgs)** system.

- **English units** (also known as the customary or imperial system). English units were historically used in nations once ruled by the British Empire and are still widely used in the United States.

- The English system may also be referred to as the **the foot–pound–second (fps)** system.

- In any system of units, the units for some physical quantities must be defined through a measurement process. These are called the **base quantities** for that system

- The base quantities units are the system's **base units**

- All other physical quantities can then be expressed as algebraic combinations of the base quantities. Each of these physical quantities is then known as a **derived quantity** and each unit is called a **derived unit.**

- A **conversion factor** is a ratio that expresses how many of one unit are equal to another unit.

- The **dimension** of any physical quantity expresses its dependence on the base quantities as a product of symbols (or powers of symbols) representing the base quantities.

- Any quantity with a dimension that can be written so that all seven powers are zero (that is, its dimension is $L^0 M^0 T^0 I^0 \Theta^0 N^0 J^0$) is called **dimensionless** (or sometimes "of dimension 1," because anything raised to the zero power is one).

- Physicists often call dimensionless quantities **pure numbers**.

- The importance of the concept of dimension arises from the fact that any mathematical equation relating physical quantities must be **dimensionally consistent**

- – Every term in an expression must have the same dimensions; it does not make sense to add or subtract quantities of differing dimension (think of the old saying: "You can't add apples and oranges"). In particular, the expressions on each side of the equality in an equation must have the same dimensions.

- – The arguments of any of the standard mathematical functions such as trigonometric functions (such as sine and cosine), logarithms, or exponential functions that appear in the equation must be dimensionless. These functions require pure numbers as inputs and give pure numbers as outputs.

- **Estimation** means using prior experience and sound physical reasoning to arrive at a rough idea of a quantity's value.

- **Accuracy** is how close a measurement is to the accepted reference value for that measurement.

- The **precision of measurements** refers to how close the agreement is between repeated independent measurements (which are repeated under the same conditions).

- The precision of a measuring system is related to the **uncertainty** in the measurements whereas the accuracy is related to the **discrepancy** from the accepted reference value.

- **Discrepancy** (or "measurement error") is the difference between the measured value and a given standard or expected value.

- Another method of expressing uncertainty is as a percent of the measured value.

2.1.2 Defintions and Theorems (and important things)

- **Order of Magnitude (Method one)**

$$m = \log_{10} l, \; l \in \mathbb{R}.$$

For example

$$\log 450 \approx 3.$$

Thus the order of magnitude is 10^3

Note: Always round s.t $m \in \mathbb{R}$

- **Order of Magnitude (Method two)**: We begin by writing the number in scientific notation. For example, suppose we want to find the order of magnitude for 800, we first write

$$8 \cdot 10^2.$$

We then check to see if the first factor is greater or less than $\sqrt{10} \approx 3$

  − If it is less than $\sqrt{10} \approx 3$, we round it down to one
  − If it is greater than $\sqrt{10} \approx 3$, we round it up to ten

Since 8 is greater than $\sqrt{10} \approx 3$, our number becomes $10 \cdot 10^2 = 10^{2+1} = 10^3$. Thus, we have order 10^3

- The SI unit for time is the **second**

- The SI unit for length is the **meter**

- The SI unit for mass is the **kilogram**

- The SI unit for weight is the **Newton**

- 10^3 **(Megagram) is also called a** *metric ton***, abbreviated** t

- **Average speed**

$$\frac{\text{distance}}{\text{time}} = \frac{d}{t}.$$

- **Dimension notation**: Square brackets

$$[r] = L.$$

- **Checking for dimensional consistency**: check that each term in a given equation has the same dimensions as the other terms in that equation and that the arguments of any standard mathematical functions are dimensionless.

- **Dimension for velocity**

$$[v] = LT^{-1}.$$

- **Dimension for acceleration**

$$[a] = LT^{-2}.$$

- **Dimensions for derivatives**

$$\left[\frac{dv}{dt}\right] = \frac{[v]}{[t]}.$$

- **Dimensions for integrals**

$$\left[\int v\,dt\right] = [v]\cdot[t]..$$

- **Volume**

$$V = AD.$$

Where A is the area and D is the depth

- **Mass**

$$M = \rho V.$$

Where ρ is the density and V is the volume

- **Density (Volume density)**

$$\rho = \frac{M}{V}.$$

Where M is the mass and V is the volume

- **Density (Area density)**

$$\rho = \frac{M}{A}.$$

Where M is the mass and A is the surface area

- **Geometric mean of bounds**

$$(order_1 \times order_2)^{0.5}.$$

- **Significant figures**:

  - All non-zero numbers are Significant.

  $$563 \rightarrow 3.$$

  - Zeros are significant if they reside between two significant figures.

  $$5002 \rightarrow 4.$$

  - Leading zeros are never significant.

  $$0.0056 \rightarrow 2.$$

  - Trailing zeros without a decimal point are not significant

  $$500 \rightarrow 1.$$

  - Trailing zeros with a decimal point are significant. The decimal point indicates that the zeros are measured and are significant.

  $$500.0 \rightarrow 4.$$

- **Percent uncertainty**: If a measurement A is expressed with uncertainty δA, the percent uncertainty is defined as

$$\text{Percent uncertainty} = \frac{\delta A}{A} \times 100\%.$$

where A is the average, and δA is the margin of error

Note: The value of the PU will take the place of the margin of error, so something like 5.1 *lbs* $\pm$ 0.3 *lbs* will become $5.1 \pm 6\%$

- **We can find the margin of error (δA) by taking half of the range**

- **If the measurements going into the calculation have small uncertainties (a few percent or less), then the method of adding percents can be used for multiplication or division. This method states the percent uncertainty in a quantity calculated by multiplication or division is the sum of the percent uncertainties in the items used to make the calculation. For example, if a floor has a length of** $4.00\,\text{m}$ **and a width of** $3.00\,\text{m}$**, with uncertainties of** 2% **and** 1%**, respectively, then the area of the floor is** $12.0\,\text{m}^2$ **and has an uncertainty of** 3%**. (Expressed as an area, this is** $0.36\,\text{m}^2$ $[12.0\,\text{m}^2 \times 0.03]$**, which we round to** $0.4\,\text{m}^2$ **since the area of the floor is given to a tenth of a square meter.)**

- **When combining measurements with different degrees of precision with the mathematical operations of addition, subtraction, multiplication, or division, then the number of significant digits in the final answer can be no greater than the number of significant digits in the least-precise measured value. There are two different rules, one for multiplication and division and the other for addition and subtraction. There are two different rules**

  - **For multiplication and division**, the result should have the same number of significant figures as the quantity with the least number of significant figures entering into the calculation

  - **For addition and subtraction**, the answer can contain no more decimal places than the least-precise measurement.

- **If a quantity increases n%, that is the same as saying that it is multiplied by a factor of**

$$1 + \left(\frac{n}{100}\right).$$

- **If a quantity decreases n%, that is the same as saying that it is multiplied by a factor of**

$$1 - \left(\frac{n}{100}\right).$$

- **Proportional notation**: Suppose A is proportional to B, then we say

$$A\alpha B.$$

This means if B increases by some factor, then A must increase by the same factor.

In other words, the ratio of two values of B is equal to the ratio of the corresponding values of A:

$$\frac{B_2}{B_1} = \frac{A_2}{A_1}.$$

Ex: Given the circumference formula for a circle

$$c = 2\pi r.$$

We can say

$$C\alpha r.$$

If the radius doubles, the circumference also doubles

- **Numbers that are exact (defined) have an infinite number of significant figures** because they are not measurements with any uncertainty, but rather are defined values or counts of discrete objects. For example, considering a conversion of 93.4 beats/min to beats/hour, we would compute

$$\frac{93.4 \ beats}{1 \ m} \cdot \frac{60 \ m}{1 \ h}$$
$$= 5604 \ b/h.$$

  Since the number 60 is an exact number (it is a defined conversion factor), we should report the answer with three significant figures (since 93.4 has three). Thus, we round to 5600. To explicitly express 5600 with three sig figs, we write as $5.60 \cdot 10^3$

- **Explicity express sig figs with scientific notation**

$$5600 \to 2$$
$$5.60 \cdot 10^3 \to 3.$$

- **Forms of scientific notation**

$$10^{10} = 1.0 \cdot 10^{10} = 1.0e + 10.$$

- **Decimal places in additon and subtraction**: consider the example

$$501.258313 + 54.5235 + 350.257 = 906.038813.$$

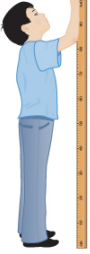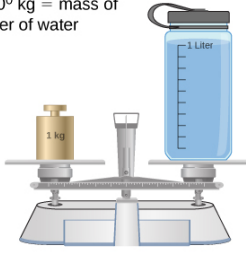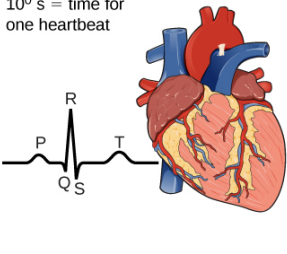 We would report the value as

$$906.039.$$

  Because the least precise measurement has three decimal points

- unless you are working on lab-related calculations (ie in your lab reports) or the question explicitly asks you to pay attention to sig figs, **you can err on the side of including extra ones**

- **Weight is the measure of the force exerted on an object due to gravity. It is calculated as the mass of the object multiplied by the acceleration due to gravity.**

- **Newton**

$$N = kg \cdot \frac{m}{s^2}.$$

2.1.3 Fundemental Tables and figures

- **Known ranges of length, mass, and time**

Length in Meters (m)	Masses in Kilograms (kg)	Time in Seconds (s)
10^{-15} m = diameter of proton	10^{-30} kg = mass of electron	10^{-22} s = mean lifetime of very unstable nucleus
10^{-14} m = diameter of large nucleus	10^{-27} kg = mass of proton	10^{-17} s = time for single floating-point operation in a supercomputer
10^{-10} m = diameter of hydrogen atom	10^{-15} kg = mass of bacterium	10^{-15} s = time for one oscillation of visible light
10^{-7} m = diameter of typical virus	10^{-5} kg = mass of mosquito	10^{-13} s = time for one vibration of an atom in a solid
10^{-2} m = pinky fingernail width	10^{-2} kg = mass of hummingbird	10^{-3} s = duration of a nerve impulse
10^0 m = height of 4 year old child	10^0 kg = mass of liter of water	10^0 s = time for one heartbeat
10^2 m = length of football field	10^2 kg = mass of person	10^5 s = one day
10^7 m = diameter of Earth	10^{19} kg = mass of atmosphere	10^7 s = one year
10^{13} m = diameter of solar system	10^{22} kg = mass of Moon	10^9 s = human lifetime
10^{16} m = distance light travels in a year (one light-year)	10^{25} kg = mass of Earth	10^{11} s = recorded human history
10^{21} m = Milky Way diameter	10^{30} kg = mass of Sun	10^{17} s = age of Earth
10^{26} m = distance to edge of observable universe	10^{53} kg = upper limit on mass of known universe	10^{18} s = age of the universe

- **SI Units: Base and Derived Units**

ISQ Base Quantity	SI Base Unit
Length	meter (m)
Mass	kilogram (kg)
Time	second (s)
Electrical current	ampere (A)
Thermodynamic temperature	kelvin (K)
Amount of substance	mole (mol)
Luminous intensity	candela (cd)

- **Metric Prefixes**

Prefix	Symbol	Meaning	Prefix	Symbol	Meaning
yotta-	Y	10^{24}	yocto-	y	10^{-24}
zetta-	Z	10^{21}	zepto-	z	10^{-21}
exa-	E	10^{18}	atto-	a	10^{-18}
peta-	P	10^{15}	femto-	f	10^{-15}
tera-	T	10^{12}	pico-	p	10^{-12}
giga-	G	10^{9}	nano-	n	10^{-9}
mega-	M	10^{6}	micro-	μ	10^{-6}
kilo-	k	10^{3}	milli-	m	10^{-3}
hecto-	h	10^{2}	centi-	c	10^{-2}
deka-	da	10^{1}	deci-	d	10^{-1}

- **Base Quantity & Symbol for Dimension**

Base Quantity	Symbol for Dimension
Length	L
Mass	M
Time	T
Current	I
Thermodynamic temperature	Θ
Amount of substance	N
Luminous intensity	J

2.1.4 Memorize conversions

- **Newton to Pounds**:

$$1N = 0.225lbs.$$

- **Pounds to newtons**

$$1lb = 4.448 \ N.$$

- **Length/Distance**

  - 1 inch (in) = 2.54 centimeters (cm)
  - 1 centimeter (cm) = 0.393701 inches (in)
  - 1 foot (ft) = 0.3048 meters (m)
  - 1 meter (m) = 3.28 feet (ft)
  - 1 mile (mi) = 1.6 kilometers (km)
  - 1 kilometer (km) = 0.621371 miles (mi)

- **Weight to mass or mass to weight**

  - 1 pound = 0.453592 kilograms.
  - 1 kilogram = 2.2 pounds.

2.1.5   Problems to remember

- **Restating mass**: Restate the mass 1.93×10^{13} using a metric prefix such that the resulting numerical value is bigger than one but less than 1000.

  First, we must restate in terms of grams. Since $1kg = 10^3 g$, we write

  $$1.93 \times 10^{13} \times 10^3 g$$
  $$1.93 \times 10^{16} g.$$

  Since $1Pg = 10^{15}g$, we can write

  $$1.93 \times 10^1 Pg.$$

  Since $16 - 15 = 1$

- **Unit conversion**: The distance from the university to home is 10 mi and it usually takes 20 min to drive this distance. Calculate the average speed in meters per second (m/s). (Note: Average speed is distance traveled divided by time of travel.)

  Note: There are 1609 meters in 1 mile

  First, we can compute the average speed with the units given $\left(\frac{miles}{minute}\right)$

  $$\text{Average Speed} = \frac{\text{miles}}{\text{minute}} = \frac{10}{20} = 0.5 \ mi/min.$$

  Now we simply convert to m/s

  $$\frac{0.5 \ \cancel{mi}}{1 \ \cancel{min}} \times \frac{1 \ \cancel{min}}{60 \ sec} \times \frac{1609 \ m}{1 \ \cancel{mi}}$$
  $$\approx 13 m/s.$$

- **Unit conversion**: The density of iron is $7.86 g/cm^3$ under standard conditions. Convert this to kg/m^3.

  $$\frac{7.86 \ g}{1 \ cm^3} \times \left(\frac{100 \ cm}{1 \ m}\right)^3 \times \frac{1 \ kg}{1000 \ g}$$
  $$= \frac{7.86(100^3)(1 \ kg)}{1000(1 \ m)}$$
  $$= 7.86 \cdot 10^3 kg/m^3.$$

- **Proportional**: I found that if I drive my car 110 miles, I use 4 gallons of gas. If I assume that the relationship between gas guzzled and distance driven is linearly proportional, how many gallons of gas do I use if I drive 275 miles?

  To answer this lets find the linear equation

  $$4 \ gal = k(100 \ mi).$$

  Where k is some arbitrary factor, Since we know the relationship is proportional, we can write

  $$\frac{X}{4gal} = \frac{k(275 \ mi)}{k(110 \ mi)}$$
  $$X = 10 \ gal.$$

2.2   Chapter 2: Vectors

2.2.1   Vocabulary

- Many familiar physical quantities can be specified completely by giving a single number and the appropriate unit. For example, "a class period lasts 50 min" or "the gas tank in my car holds 65 L" or "the distance between two posts is 100 m." A physical quantity that can be specified completely in this manner is called a **scalar quantity**. Scalar is a synonym of "number." Time, mass, distance, length, volume, temperature, and energy are examples of **scalar quantities**.

- possible. Physical quantities specified completely by giving a number of units (magnitude) and a direction are called **vector quantities**. Examples of vector quantities include displacement, velocity, position, force, and torque.

2.2.2   Definitions and theorems (and important things)

- Vectors (vector quantities) have a **number of units (magnitude)**, and a **direction**

- **Algebraic Operations with vectors**

    - We can **add or subtract** two vectors
    - we can **multiply** a vector by a scalar or by another vector
    - We **cannot** divide by a vector. The operation of division by a vector is not defined.

- **Vector Notation**: We denote a vector with a bold face letter with an arrow above it. For example

$$\vec{\mathbf{V}}.$$

- **Displacement**: General term used to describe change in position.

- **The magnitude of a vector is the length of the arrow used to represent it**

- **Vector relations**
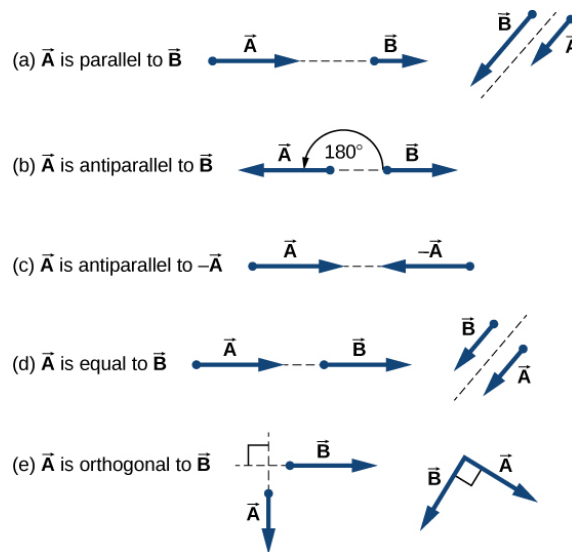
- **Scalars**: When a vector $\vec{A}$ is multiplied by a positive scalar α, the result is a new vector $\vec{B}$ that is parallel to $\vec{A}$:

$$\vec{\mathbf{B}} = \alpha\vec{\mathbf{A}}.$$

The magnitude of this new vector $\vec{\mathbf{B}}$ is

$$B = |\alpha|A.$$

Where B is the magnitude of $\vec{\mathbf{B}}$ and A is the magnitude of $\vec{\mathbf{A}}$

- **Anti parallel vectors (opposing directions)**: Suppose we have two vectors $\vec{\mathbf{A}}$ and $\vec{\mathbf{B}}$ of equal magnitude. If there are antiparallel, we write

$$\vec{\mathbf{A}} = -\vec{\mathbf{B}}.$$

- The vector sum of two (or more) vectors is called the **resultant vector** or, for short, the **resultant**

- The vector obtained by adding two vectors is called the **resultant**

- **Vector Laws**

  - **Communitive law**: $\vec{A} + \vec{B} = \vec{B} + \vec{A}$
  - **Assosiative law**: $(\vec{A} + \vec{B}) + \vec{C} = \vec{A} + (\vec{B} + \vec{C})$
  - **Distributive law**: $\alpha_1 \vec{A} + \alpha_2 \vec{A} = (\alpha_1 + \alpha_2)\vec{A}$

- **Vector addition**

$$\vec{\mathbf{A}} + \vec{\mathbf{B}}.$$

When two vectors are parallel, we can simply sum their magnitudes. However, if the vectors lie in different directions, the approach for vector addition involves finding their x and y components, summing them and then finding the magnitude.

- **Vector Subtraction**

$$\vec{\mathbf{A}} + (-\vec{\mathbf{B}}).$$

When two vectors are aligned but point in exactly opposite directions, you can subtract their magnitudes (assuming you define one direction as positive and the other as negative) to find the net effect. This is a specific case of adding magnitudes where the direction is implicitly considered through subtraction.

- **Unit Vector notation**: A unit vector in a normed vector space is a vector of length 1. We declare unit vectors with a hat instead of an arrow, consider the following example

$$\hat{\mathbf{u}}.$$

We usually denote the unit vector along the positive x-axis $\hat{i}$, the unit vector along the positive y-axis $\hat{j}$, and the unit vector along the positive z-axis $\hat{k}$

- **Unit vector example**: For example, instead of saying vector $\vec{D}_{AB}$ has a magnitude of 6.0 km and a direction of northeast, we can introduce a unit vector $\hat{u}$ that points to the northeast and say succinctly that $\vec{D}_{AB} = (6.0\,\text{km})\hat{u}$. Then the southwesterly direction is simply given by the unit vector $-\hat{u}$. In this way, the displacement of 6.0 km in the southwesterly direction is expressed by the vector

$$\vec{D}_{BA} = (-6.0\,\text{km})\hat{u}..$$

- **Parallelogram rule for resultant or difference vectors in two dimensions.**:

(a)   (b)
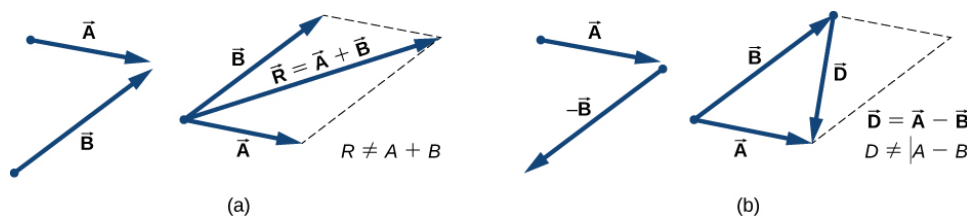
It follows from the parallelogram rule that neither the magnitude of the resultant vector nor the magnitude of the difference vector can be expressed as a simple sum or difference of magnitudes A and B, because the length of a diagonal cannot be expressed as a simple sum of side lengths.

- **tail-to-head geometric construction**

(a)   (b)
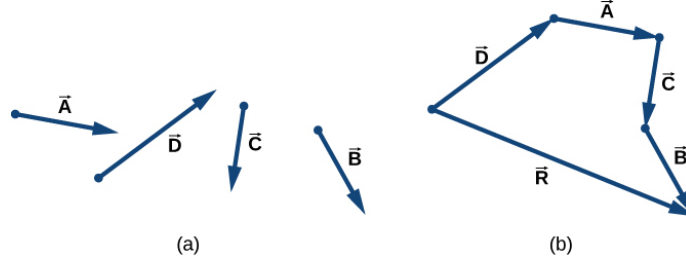
- **Vector x and y components**: The x component can be denoted, $\vec{A}_x$ the y component can be denoted $\vec{A}_y$. Thus, the vector can be represented as

$$\vec{A} = \vec{A}_x + \vec{A}_y.$$

- **Unit vectors of the axes**: It is customary to denote the positive direction on the x-axis by the unit vector $\hat{i}$ and the positive direction on the y-axis by the unit vector $\hat{j}$. Unit vectors of the axes, $\hat{i}$ and $\hat{j}$, define two orthogonal directions in the plane. The x- and y- components of a vector can now be written in terms of the unit vectors of the axes:

$$\begin{cases} \vec{A}_x & = A_x \hat{i} \\ \vec{A}_y & = A_y \hat{j} \end{cases} \tag{18}$$

- **Component form of a vector**:

$$\vec{A} = A_x \hat{i} + A_y \hat{j}.$$

- **Finding components given initial and terminal points**: If we know the coordinates $b(x_b, y_b)$ of the origin point of a vector (where b stands for "beginning") and the coordinates $e(x_e, y_e)$ of the end point of a vector (where e stands for "end"), we can obtain the scalar components of a vector simply by subtracting the origin point coordinates from the end point coordinates:

$$A_x = x_e - x_b$$
$$A_y = y_e - y_b.$$

- **Magnitude A of a vector with components A_x and A_y**

$$A^2 = A_x^2 + A_y^2$$
$$A = \sqrt{A_x^2 + A_y^2}.$$

This equation works even if the scalar components of a vector are negative.

- **Finding theta for a vector (used for direction angles)**

$$\tan \theta = \frac{A_y}{A_x}.$$

- **Direction angles for vectors in the first**:

- **Direction angles for vectors in the second quadrant**:

$$\theta_A = \theta.$$

- **Direction angles for vectors in the second quadrant**:

$$\theta_A = 180 - \theta.$$

- **Direction angles for vectors in the second quadrant**:

$$\theta_A = 180 + \theta.$$

- **Direction angles for vectors in the fourth quadrant**:

$$\theta_A = 360 - \theta.$$

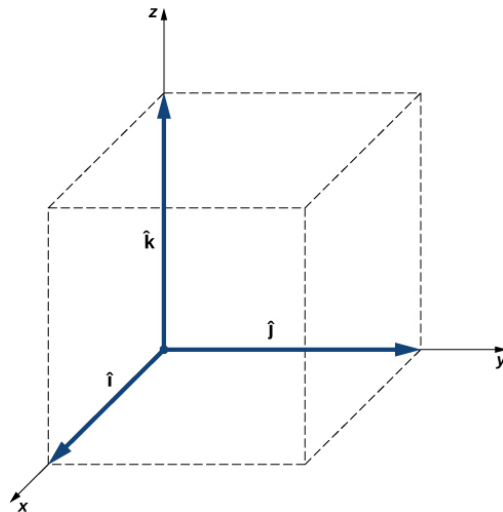- **Finding A_x and A_y when the magnitude and direction angle are known**

$$\begin{cases} A_x = A \cos \theta_A \\ A_y = A \sin \theta_A \end{cases} \tag{19}$$

- **Polar form**

$$x = r \cos \varphi$$
$$y = r \sin \varphi.$$

- **Three dimensional plane**

- z **component of a vector**:

$$\vec{A}_z = A_z \hat{k}.$$

Where A_z is given by

$$z_e - z_b.$$

- **Vector in three dimensions**: A vector in three-dimensional space is the vector sum of its three vector component.

$$\vec{A} = A_x\hat{i} + A_y\hat{j} + A_z\hat{k}..$$

- **Magnitude of a vector in three dimensions**

$$A = \sqrt{A_x^2 + A_y^2 + A_z^2}..$$

- **Null vector**: Denoted by

$$\vec{0}.$$

Has all components 0. Thus,

$$\vec{0} = 0\hat{i} + 0\hat{j} + 0\hat{k}.$$

Thus, it has no direction and no length

- Two vectors $\vec{A}$ and $\vec{B}$ are **equal vectors** if and only if their difference is the null vector: Hence, we can write $\vec{A} = \vec{B}$ if and only if the corresponding components of vectors $\vec{A}$ and $\vec{B}$ are equal:

$$\vec{A} = \vec{B} \Leftrightarrow \begin{cases} A_x = B_x \\ A_y = B_y \\ A_z = B_z \end{cases}$$

- **Components of a resultant vector**:

$$\begin{cases} R_x = A_x + B_x \\ R_y = A_y + B_y \\ R_z = A_z + B_z \end{cases} \tag{20}$$

- **components of a resultant of many vectors**: if we are to sum up N vectors $\vec{F_1}, \vec{F_2}, \vec{F_3}, \dots, \vec{F_N}$, where each vector is $\vec{F_k} = F_{kx}\hat{i} + F_{ky}\hat{j} + F_{kz}\hat{k}$, the resultant vector $\vec{F_R}$ is

$$\begin{cases} F_{R_x} = \sum_{k=1}^{N} F_{kx} = F_{1x} + F_{2x} + F_{3x} + \dots + F_{Nx} \\ F_{R_y} = \sum_{k=1}^{N} F_{ky} = F_{1y} + F_{2y} + F_{3y} + \dots + F_{Ny} \\ F_{R_z} = \sum_{k=1}^{N} F_{kz} = F_{1z} + F_{2z} + F_{3z} + \dots + F_{Nz} \end{cases} \tag{21}$$

With the component form

$$\vec{F_R} = F_{R_x}\hat{i} + F_{R_y}\hat{j} + F_{R_z}\hat{k}.$$

- **Finding unit vector (Direction) of some vector**: Suppose we have some vector $\vec{V}$. Then

$$\hat{V} = \frac{\vec{V}}{V}.$$

- **Dot product**

$$\vec{A} \cdot \vec{B} = AB\cos\varphi.$$

Where φ is the angle between the vectors

- **Dot product of two parallel vectors**

$$\vec{A} \cdot \vec{B} = AB \cos 0° = AB.$$

- **Dot product of two anti-parallel vectors**

$$\vec{A} \cdot \vec{B} = AB \cos 180° = -AB.$$

- **Dot product of two orthogonal vectors**

$$\vec{A} \cdot \vec{B} = AB \cos 90° = 0.$$

- **Dot product of a vector with itself**

$$\vec{A} \cdot \vec{A} = AA \cos 0 = A^2.$$

- **Dot products of unit vectors**: Scalar products of the unit vector of an axis with other unit vectors of axes always vanish (equals 0) because these unit vectors are orthogonal:

- **Dot product of the same unit vector**: The dot product of the same unit vector is 1

$$\hat{i} \cdot \hat{i} = i^2 = 1.$$

- **Using dot product to find scalar x-component**

$$\vec{A} \cdot \hat{i} = \|\vec{A}\| \|\hat{i}\| \cos \theta_A = A \cos \theta_A = A_x.$$

- **Using dot product to find scalar y-component**

$$\vec{A} \cdot \hat{j} = \|\vec{A}\| \|\hat{j}\| \cos (90° - \theta_A) = A \sin \theta_A = A_y.$$

- **Trig complementary angles**: For a right angle triangle, the sine of the complemenary angle is the cosine of the angle. And vice versa

$$\sin 90 - \theta = \cos \theta$$
$$\cos 90 - \theta = \sin \theta.$$

- **Dot product second method of computation**

$$\vec{A} \cdot \vec{B} = A_x B_x + A_y B_y + A_z B_z.$$

- **Equation for** $\cos (\varphi)$

$$\cos (\varphi) = \frac{\vec{A} \cdot \vec{B}}{AB}.$$

- The **Si unit for work** is the joule (J), where

$$1 \text{ J} = 1 \text{ N} \cdot \text{m}.$$

- **The Work of a Force**: When force $\vec{F}$ pulls on an object and when it causes its displacement $\vec{D}$, we say the force performs work. The amount of work the force does is the scalar product $\vec{F} \cdot \vec{D}$.

- **Cross Product (Vector Product)**: The vector product of two vectors $\vec{A}$ and $\vec{B}$ is denoted by $\vec{A} \times \vec{B}$ and is often referred to as a cross product. The vector product is a vector that has its direction perpendicular to both vectors $\vec{A}$ and $\vec{B}$. In other words, vector $\vec{A} \times \vec{B}$ is perpendicular to the plane that contains vectors $\vec{A}$ and $\vec{B}$. The magnitude of the vector product is defined as

$$\|\vec{A} \times \vec{B}\| = AB \sin \varphi, \tag{22}$$

where angle φ, between the two vectors, is measured from vector $\vec{A}$ (first vector in the product) to vector $\vec{B}$ (second vector in the product), as indicated in Figure 2.29, and is between $0°$ and $180°$.

- The **vector product vanishes** for pairs of vectors that are either **parallel** ($\varphi = 0°$) or **antiparallel** ($\varphi = 180°$) because $\sin 0° = \sin 180° = 0$.

- The cross product is **anti-communitive**

$$\vec{A} \times \vec{B} = -\vec{B} \times \vec{A}..$$

- **Torque**: Denoted with the greek letter "tau" is the vector product of the distance between the pivot to force with the force:

$$\vec{\tau} = \vec{R} \times \vec{F}.$$

- **the cross product has the following distributive property:**

$$\vec{A} \times (\vec{B} + \vec{C}) = \vec{A} \times \vec{B} + \vec{A} \times \vec{C}.$$

- **Cross product of the same unit vectors**: The cross product of the same unit vectors is 0

- **Cross product between unit vectors**

$$\begin{cases} \hat{i} \times \hat{j} = +\hat{k} \\ \hat{j} \times \hat{i} = -\hat{k} \\ \hat{j} \times \hat{k} = +\hat{i} \\ \hat{k} \times \hat{j} = -\hat{i} \\ \hat{k} \times \hat{i} = +\hat{j} \\ \hat{i} \times \hat{k} = -\hat{j} \end{cases} \tag{23}$$

Notice: The cross product of two different unit vectors is always a third unit vector.

- **Computation of the cross product**:

$$\vec{C} = \vec{A} \times \vec{B} = (A_y B_z - A_z B_y)\hat{i} + (A_z B_x - A_x B_z)\hat{j} + (A_x B_y - A_y B_x)\hat{k}.$$
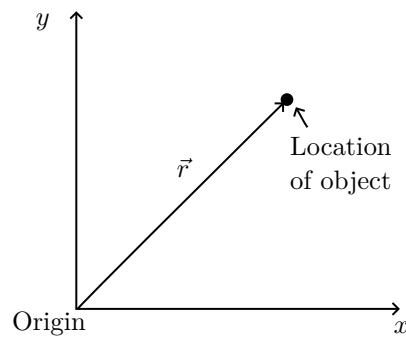
- **Average Velocity**: Velocity is the **vector quantity** of speed plus the direction. Velocity is

$$\vec{v} = \frac{\text{Displacement}}{Time} = \frac{\|\vec{d}\|}{t}.$$

Where $\|\vec{d}\|$ is the magnitude of the displacement vector, and t is the total elapsed time.

- To describe the position (location) of something, we give its distance from the orgin and its direction. This vector quantity is called the **position vector**, Denoted

$$\vec{r}.$$

- **Displacement** is defined as the change in the position vector. The final position vector minus the initial position vector

$$\Delta \vec{r} = \vec{r}_f - \vec{r}_i.$$
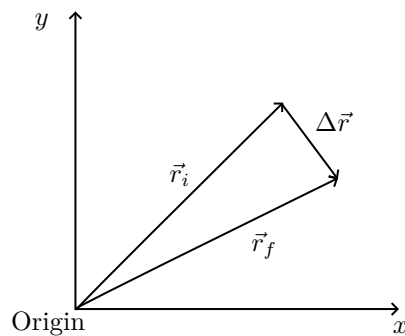
2.2.3 Problems to remember

Unit vectors: A long measuring stick rests against a wall in a physics laboratory with its 200-cm end at the floor. A ladybug lands on the 100-cm mark and crawls randomly along the stick. It first walks 15 cm toward the floor, then it walks 56 cm toward the wall, then it walks 3 cm toward the floor again. Then, after a brief stop, it continues for 25 cm toward the floor and then, again, it crawls up 19 cm toward the wall before coming to a complete rest (Figure 2.8). Find the vector of its total displacement and its final resting position on the stick.

If we choose the direction along the stick toward the floor as the direction of unit vector $\hat{u}$, then the direction toward the floor is $+\hat{u}$ and the direction toward the wall is $-\hat{u}$. The ladybug makes a total of five displacements:

$$\vec{D}_1 = (15\,\text{cm})(+\hat{u}), \quad \vec{D}_2$$
$$= (56\,\text{cm})(-\hat{u}), \quad \vec{D}_3$$
$$= (3\,\text{cm})(+\hat{u}), \quad \vec{D}_4$$
$$= (25\,\text{cm})(+\hat{u}), \quad \text{and} \quad \vec{D}_5$$
$$= (19\,\text{cm})(-\hat{u})..$$

The total displacement $\vec{D}$ is the resultant of all its displacement vectors.

The resultant of all the displacement vectors is

$$\vec{D} = \vec{D}_1 + \vec{D}_2 + \vec{D}_3 + \vec{D}_4 + \vec{D}_5$$
$$= (15\,\text{cm})(+\hat{u}) + (56\,\text{cm})(-\hat{u}) + (3\,\text{cm})(+\hat{u}) + (25\,\text{cm})(+\hat{u}) + (19\,\text{cm})(-\hat{u})$$
$$= (15 - 56 + 3 + 25 - 19)\,\text{cm}\,\hat{u} = -32\,\text{cm}\,\hat{u}.$$

In this calculation, we use the distributive law. The result reads that the total displacement vector points away from the 100-cm mark (initial landing site) toward the end of the meter stick that touches the wall. The end that touches the wall is marked 0 cm, so the final position of the ladybug is at the $(100 - 32)\,\text{cm} = 68\,\text{cm}$ mark.

2.3   Chapter 3: Motion along a straight line

2.3.1   Definitions and theorems

- **Kinematics** is a subfield of physics, developed in classical mechanics, that describes the motion of points, bodies, and systems of bodies without considering the forces that cause them to move

- **Displacement**: Displacement Δx is the change in position of an object:

$$\Delta x = x_f - x_0, .$$

where Δx is displacement, x_f is the final position, and x_0 is the initial position.

- We define total displacement Δx_{Total}, as the sum of the individual displacements, and express this mathematically with the equation

$$\Delta x_{\text{Total}} = \sum \Delta x_i.$$

- **the distance traveled** is the sum of the magnitudes of the individual displacements:

$$x_{\text{total}} = \sum_{i=1}^{n} \Delta x_i.$$

- If the details of the motion at each instant are not important, the rate is usually expressed as the **average velocity**. If x_1 and x_2 are the positions of an object at times t_1 and t_2 , respectively, then

$$\text{Average Velocity } = \bar{v} = \frac{\text{Displacement between two points}}{\text{Time needed to make the displacement}}$$

$$\bar{v} = \frac{\Delta x}{\Delta t} = \frac{x_2 - x_1}{t_2 - t_1}.$$

This vector quantity is simply the total displacement between two points divided by the time taken to travel between them. The time taken to travel between two points is called the **elapsed time** Δt

- The **instantaneous velocity** of an object is the limit of the average velocity as the elapsed time approaches zero, or the derivative of x with respect to t:

$$v(t) = \lim_{\Delta t \to 0} \frac{f(t + \Delta t) - f(t)}{\Delta t}$$

$$= \frac{d}{dt} x(t) = \frac{d\vec{r}}{dt}..$$

- We can calculate the **average speed** by finding the total distance traveled divided by the elapsed time:

$$\text{Average speed } = \bar{s} = \frac{\text{Total distance}}{\text{Elapsed time}}..$$

- we can calculate the **instantaneous speed** from the magnitude of the instantaneous velocity:

$$\text{instantaneous speed } = \left| v(t) \right|.$$

- **Calculating Instantaneous Velocity** When calculating instantaneous velocity, we need to specify the explicit form of the position function $x(t)$. If each term in the $x(t)$ equation has the form of At^n where A is a constant and n is an integer, this can be differentiated using the power rule to be:

$$\frac{d(At^n)}{dt} = Ant^{n-1}.$$

- **Average acceleration** is the rate at which velocity changes:

$$\bar{a} = \frac{\Delta v}{\Delta t} = \frac{v_f - v_0}{t_f - t_0}, .$$

  where $\bar{a}$ is average acceleration, v is velocity, and t is time. (The bar over the a means average acceleration.)

  Note: acceleration occurs when velocity changes in magnitude (an increase or decrease in speed) or in direction, or both.

- **Acceleration as a vector:** Acceleration is a vector in the same direction as the change in velocity, Δv . Since velocity is a vector, it can change in magnitude or in direction, or both. Acceleration is, therefore, a change in speed or direction, or both.

  Keep in mind that although acceleration is in the direction of the change in velocity, it is not always in the direction of motion. When an object slows down, its acceleration is opposite to the direction of its motion. Although this is commonly referred to as deceleration

- **Distance over constant acceleration**

$$d = \frac{1}{2}at^2.$$

  Where a is the acceleration, and t is the time

- **instantaneous acceleration**

$$a(t) = \frac{d}{dt}v(t).$$

- **Derivative of velocity function**: Suppose we have some function

$$v(t) = (20m/s)t - (10m/s^2)t^2.$$

  When we find the acceleration function, we are taking the derivative of the velocity function. Thus, we are finding the change in velocity with respect to time. Consequently, our terms become

$$a(t) = 20m/s^2 - (10m/s^3)t.$$

  Notice: How we are dividing by an additional unit of time, thus the exponents for our seconds increases by one.

- **Simplified notation**: If we take initial time to be zero, and final quantitys without subscript, then we have

$$\Delta t = t$$
$$\Delta x = x - x_0$$
$$\Delta v = v - v_0$$

.

- **Assumption of constant acceleration**: This assumption allows us to avoid using calculus to find instantaneous acceleration. Since acceleration is constant, the average and instantaneous accelerations are equal—that is,

$$\bar{a} = a = \text{constant.}$$

  Thus, we can use the symbol a for acceleration at all times.

- **Final Position function**

$$x = x_0 + \bar{v}t.$$

- **Average velocity under constant acceleration**

$$\bar{v} = \frac{v_0 + v}{2} \quad \text{(Constant } a\text{).}$$

  This reflects the fact that when acceleration is constant, $\bar{v}$ is just the simple average of the initial and final velocities.

- **Final Velocity function under constant acceleration**

$$v = v_0 + at \quad \text{(Constant } a\text{).}$$

- **Equation for final position under constant acceleration**

$$x = x_0 + v_0 t + \frac{1}{2}at^2 \quad \text{(Constant } a\text{).}$$

  When initial position and velocity are both zero, we have

$$x = \frac{1}{2}at^2 \quad \text{(Constant } a\text{).}$$

- **relationships seen in final position under constant acceleration equation**

  – Displacement depends on the square of the elapsed time when acceleration is not zero.

  – If acceleration is zero, then initial velocity equals average velocity $v_0 = \bar{v}$, and $x = x_0 + v_0 t + \frac{1}{2}at^2$ becomes $x = x_0 + v_0 t$.

- **Final velocity equation (no time required)**

$$v^2 = v_0^2 + 2a(x - x_0) \quad \text{(Constant } a\text{).}$$

- **additional insights into the general relationships among physical quantities:**

  – The final velocity depends on how large the acceleration is and the distance over which it acts.

  – For a fixed acceleration, a car that is going twice as fast doesn't simply stop in twice the distance. It takes much farther to stop. (This is why we have reduced speed zones near schools.)

- **acceleration in terms of velocities and displacement**

$$a = \frac{v^2 - v_0^2}{2(x - x_0)}.$$

- **two-body pursuit problems**

- Find equations of motion for both bodies (with the same parameter)
- eliminate the parameter
- plug in knowns to solve for the unknown

- if **air resistance and friction are negligible**, then in a given location all objects fall toward the center of Earth with the same **constant acceleration, independent of their mass.**

- an object falling without air resistance or friction is defined to be in **free fall**

- The acceleration of free-falling objects is therefore called **acceleration due to gravity**

$$g = 9.8 \ m/s^2.$$

Note: If we define the upward direction as positive, then $a = g = -9.8m/s^2$, and if we define the downward direction as positive, then $a = g = 9.8m/s^2$

- **vertical displacement**: We denote vertical displacement with the symbol y

- **Kinematic equations for objects in free fall**: We assume here that acceleration equals -g (with the positive direction upward).

$$v = v_0 - gt$$
$$y = y_0 + v_0 t - \frac{1}{2}gt^2$$
$$v^2 = v_0^2 - 2g(y - y_0).$$

- **Change in velocity**

$$\Delta v = a\Delta t.$$

If you don't care about position this relates the acceleration, intervals of time and changes in velocity

- **Change in position**

$$\Delta x = \frac{1}{2}(v_f - v_i)\Delta t.$$

2.4   Chapter 4: Motion in two and three dimensions

2.4.1   Definitions and theorems

- **Location of a particle in space**

$$x = x(t)$$
$$y = y(t)$$
$$z = z(t).$$

Where x, y, z are functions of time (t).

- **Position vector in space**

$$\vec{\mathbf{r}}(t) = x(t)\hat{\mathbf{i}} + y(t)\hat{\mathbf{j}} + z(t)\hat{\mathbf{k}}.$$

- **Displacement vector in space**: Suppose we have a particle. At time t_1 the particle is located at P_1 with position vector $\vec{\mathbf{r}}(t_1)$. At some later time t_2, the particle is located at P_2 with position vector $\vec{\mathbf{r}}(t_2)$. The displacement vector $\vec{\Delta r}$ is found by subtracting $\vec{r}(t_1)$ from $\vec{r}(t_2)$:

$$\Delta\vec{\mathbf{r}} = \vec{\mathbf{r}}(t_2) - \vec{\mathbf{r}}(t_1).$$

Thus, the displacement vector $\Delta\vec{\mathbf{r}} = \vec{\mathbf{r}}(t_2) - \vec{\mathbf{r}}(t_1)$ is the vector from P_1 to P_2

- **Instantaneous velocity vector in two and three dimensions**: We can do the same operation in two and three dimensions, but we use vectors. The instantaneous velocity vector is now

$$\begin{aligned}\vec{\mathbf{v}} &= \lim_{\Delta t \to 0} \frac{\vec{\mathbf{r}}(t - \Delta t) - \vec{\mathbf{r}}(t)}{\Delta t} \\ &= \frac{d\vec{\mathbf{r}}}{dt}.\end{aligned}$$

- **Velocity in component form**

$$\vec{\mathbf{v}}(t) = v_x\hat{\mathbf{i}} + v_y\hat{\mathbf{j}} + v_z\hat{\mathbf{k}}.$$

Where

$$v_x(t) = \frac{dx(t)}{dt}, \quad v_y(t) = \frac{dy(t)}{dt}, \quad v_z(t) = \frac{dz(t)}{dt}.$$

- **Average velocity in two and three dimensions**: If only the average velocity is of concern, we have the vector equivalent of the one-dimensional average velocity for two and three dimensions

$$\vec{\mathbf{v}}_{\text{avg}} = \frac{\vec{\mathbf{r}}(t_2) - \vec{\mathbf{r}}(t_1)}{t_2 - t_1}.$$

- **The Independence of Perpendicular Motions**: When we look at the three-dimensional equations for position and velocity written in unit vector notation, we see the components of these equations are separate and unique functions of time that do not depend on one another. Motion along the x direction has no part of its motion along the y and z directions, and similarly for the other two coordinate axes. Thus, the motion of an object in two or three dimensions can be divided into separate, independent motions along the perpendicular axes of the coordinate system in which the motion takes place.

- **Independence of motion**: In the kinematic description of motion, we are able to treat the horizontal and vertical components of motion separately. In many cases, motion in the horizontal direction does not affect motion in the vertical direction, and vice versa.

- **Instantaneous Acceleration**: This acceleration vector is the instantaneous acceleration and it can be obtained from the derivative with respect to time of the velocity function. The only difference in two or three dimensions is that these are now vector quantities. Taking the derivative with respect to time $\vec{\mathbf{v}}(t)$. We find

$$\vec{\mathbf{a}}(t) = \frac{d\vec{\mathbf{v}}(t)}{dt}.$$

- **The acceleration in terms of components is**

$$\vec{\mathbf{a}}(t) = \frac{dv_x(t)}{dt}\hat{\mathbf{i}} + \frac{dv_y(t)}{dt}\hat{\mathbf{j}} + \frac{dv_z(t)}{dt}\hat{\mathbf{k}}.$$

- **acceleration in terms of the second derivative of the position function:**

$$\vec{\mathbf{a}}(t) = \frac{d^2x(t)}{dt^2}\hat{\mathbf{i}} + \frac{d^2y(t)}{dt^2}\hat{\mathbf{j}} + \frac{d^2z(t)}{dt^2}\hat{\mathbf{k}}.$$

- **Equations for position and velocity in the two and three dimensions (8)**. For simplicity I will only list the ones for the x-direction. However, keep in mind that these same equations hold for y and z

  - **Position with initial position and average velocity:**

$$x(t) = x_0 + (v_x)_{\text{avg}}\ t.$$

  - **Final velocity with initial velocity, acceleration, and time**

$$v_x(t) = v_{0x} + a_x t.$$

  - **Position**

$$x(t) = x_0 + v_{0x}t + \frac{1}{2}a_x t^2.$$

  - **Velocity with initial velocity, acceleration, final and initial position**

$$v_x^2(t) = v_{0x}^2 + 2a_x\left(x - x_0\right).$$

- **These equations can be substituted into the equations for the position and velocity vectors in component form, and velocity vector in component form without the z-component to obtain the position vector and velocity vector as a function of time in two dimensions:**

$$\vec{\mathbf{r}}(t) = x(t)\hat{\mathbf{i}} + y(t)\hat{\mathbf{j}}$$
$$\vec{\mathbf{v}}(t) = v_x(t)\hat{\mathbf{i}} + v_y(t)\hat{\mathbf{j}}.$$

- **Projectile motion** is the motion of an object thrown or projected into the air, subject only to acceleration as a result of gravity. Such objects are called **projectiles** and their path is called a **trajectory**

- **Acceleration in projectile motion**: Defining the positive direction to be upward, the components of acceleration are then very simple:

$$a_y = -9.8 \ m/s^2$$
$$a_x = 0.$$

Because gravity is vertical, $a_x = 0$. If $a_x = 0$, this means the initial velocity in the x direction is equal to the final velocity in the x direction, or $v_x = v_{0x}$

- **Kinematic equations for motion in a uniform gravitational field**

  – Horizontal motion

$$v_{0x} = v_x, \quad x = x_0 + v_x t.$$

  – **Average velocity (vertical)**
  – Basic average velocity

$$V_{y,\text{avg}} = \frac{y - y_0}{\Delta t}.$$

  – **Average velocity in special conditions**

$$V_{y,\text{avg}} = \frac{v_i + v_f}{2}.$$

  Note: gives the same result for average velocity in scenarios of uniform acceleration, such as projectile motion or free fall, under specific conditions. This formula calculates the average of the initial and final velocities, assuming that the acceleration is constant throughout the motion. It works perfectly for the vertical component of projectile motion when considering the ascent or descent separately, or any motion where the start and end points are symmetrical in terms of velocity but in opposite directions (e.g., going up and coming back down to the same height).

  – Vertical motion

$$y = y_0 + \frac{1}{2}(v_{0y} + v_y)t$$
$$v_y = v_{0y} + gt$$
$$y = y_0 + v_{0y}t + \frac{1}{2}gt^2$$
$$v_y^2 = v_{0y}^2 + 2g(y - y_0).$$

- **Projectile motion max height**

$$h = \frac{v_{0y}^2}{2g}.$$

  This equation defines the maximum height of a projectile above its launch position and it depends only on the vertical component of the initial velocity.

- **Parabolic trajectory**: If the motion is parabolic, we should use the equation with t^2 to solve for t and vertical displacement

- **Time of flight**: We can solve for the time of flight of a projectile that is both launched and impacts on a flat horizontal surface by performing some manipulations of the kinematic equations. We note the position and displacement in y must be zero

at launch and at impact on an even surface. Thus, We set the displacement in y equal to zero and find

$$T_{\text{tof}} = \frac{2(v_0 \sin \theta_0)}{g}.$$

Note: This is the time of flight for a projectile both launched and impacting on a flat horizontal surface. This equation does not apply when the projectile lands at a different elevation than it was launched,

- **Trajectory**: The trajectory of a projectile can be found by eliminating the time variable t from the kinematic equations for arbitrary t and solving for $y(x)$. We take $x_0 = y_0 = 0$ so the projectile is launched from the origin.

$$y = (\tan \theta_0)x - \left[\frac{g}{2(v_0 \cos \theta_0)^2} \right] x^2.$$

Note: This trajectory equation is of the form $y = ax + bx^2$ which is an equation of a parabola with coefficients

$$a = \tan \theta_0, \quad b = -\frac{g}{2(v_0 \cos \theta_0)^2}.$$

- **Range**: From the trajectory equation we can also find the range, or the horizontal distance traveled by the projectile.

$$R = \frac{v_0^2 \sin (2\theta_0)}{g}.$$

- **Note:** the last three equations (**time of flight, trajectory, and range**) are derived with g as negative, thus we do not make g negative when plugging into the equation.

- **Centripetal Acceleration**: a particle moving in a circle at a constant speed has an acceleration with magnitude

$$a_c = \frac{v^2}{r}.$$

Note: The direction of the acceleration vector is toward the center of the circle

- **Position vector for a particle executing circular motion**: As the particle moves on the circle, its position vector sweeps out the angle θ with the x-axis. Vector $\vec{r}(t)$ making an angle θ with the x-axis is shown with its components along the x- and y-axes. The magnitude of the position vector is $A = |\vec{r}(t)|$ and is also the radius of the circle, so that in terms of its components,

$$\mathbf{\vec{r}}(t) = A \cos(\omega t)\hat{\mathbf{i}} + A \sin(\omega t)\hat{\mathbf{j}}.$$

- **Average speed for circular motion**: If T is the item it takes to go around the circle once, and the distance around a circle is $2\pi r$, then

$$v = \frac{2\pi r}{T}$$
$$\implies T = \frac{2\pi r}{v}.$$

- **Amplitude** (A): In the contex of uniform circle motion, we define the amplitude A as the radius of the circle. Thus,

$$A = r.$$

- **Angular frequency**: In the previous equation, ω is a constant called the angular frequency of the particle.

The angular frequency has units of radians (rad) per second and is simply the number of radians of angular measure through which the particle passes per second. The angle θ that the position vector has at any particular time is ωt

- **Angular frequency computation**: If T is the period of motion, or the time to complete one revolution (2π rad), then

$$\omega = \frac{2\pi}{T}.$$

- **Example: Finding ω**: A flywheel is rotating at 21 rev/s. What is the total angle, in radians, through which a point on the flywheel rotates in 37 s?

  To find ω, we must first deduce T, if we complete 21 revolutions in one second, then the time to complete one revolution is $\frac{1}{21}s$. Thus, we have ω as

$$\frac{2\pi}{\frac{1}{21}} = 41\pi.$$

  Which gives us

$$\theta = \omega t$$
$$= 41\pi(37s).$$

- **Finding θ with ω**

$$\theta = \omega t.$$

- **Velocity for circular motion**

$$\vec{\mathbf{v}}(t) = \frac{d\vec{\mathbf{r}}(t)}{dt} = -A\omega \sin{(\omega t)}\hat{\mathbf{i}} + A\omega \cos{(\omega t)}\hat{\mathbf{j}}.$$

- **Acceleration for circular motion**

$$\vec{\mathbf{a}}(t) = \frac{d\vec{\mathbf{v}}(t)}{dt} = -A\omega^2 \cos{(\omega t)}\hat{\mathbf{i}} - A\omega^2 \sin{(\omega t)}\hat{\mathbf{j}}.$$

  From this equation we see that the acceleration vector has magnitude $A\omega^2$ and is directed opposite the position vector, toward the origin, because $\vec{a}(t) = -\omega^2 \vec{r}(t)$.

- **Nonuniform Circular Motion Tangential Acceleration**: Circular motion does not have to be at a constant speed. A particle can travel in a circle and speed up or slow down, showing an acceleration in the direction of the motion.

  In uniform circular motion, the particle executing circular motion has a constant speed and the circle is at a fixed radius. If the speed of the particle is changing as well, then we introduce an additional acceleration in the direction tangential to the circle. Such accelerations occur at a point on a top that is changing its spin rate, or any accelerating rotor. If the speed of the particle is changing, then it has a **tangential acceleration** that is the time rate of change of the magnitude of the velocity

$$a_T = \left| \frac{d\vec{\mathbf{v}}}{dt} \right|.$$

- **Tangential acceleration total acceleration**: The direction of tangential acceleration is tangent to the circle whereas the direction of centripetal acceleration is radially inward toward the center of the circle. Thus, a particle in circular motion with a tangential acceleration has a total acceleration that is the vector sum of the centripetal and tangential accelerations

$$\vec{\mathbf{a}} = \vec{\mathbf{a}}_c + \vec{\mathbf{a}}_T.$$

Thus total acceleration can be found by finding the magnitude of this vector

$$\|\vec{\mathbf{a}}\| = \sqrt{\vec{\mathbf{a}}_c^2 + \vec{\mathbf{a}}_T^2}.$$

With

$$\tan\theta = \frac{y}{x}.$$

- **Reference frames:** When we say an object has a certain velocity, we must state it has a velocity with respect to a given reference frame. In most examples we have examined so far, this reference frame has been Earth.

- **Relative Motion in One Dimension Example**: Consider an example of a person sitting in a train moving east. If we choose east as the positive direction and Earth as the reference frame, then we can write the velocity of the train with respect to the Earth as $\vec{v}_{\mathrm{TE}} = 10\,\mathrm{m/s}\,\hat{i}$ east, where the subscripts TE refer to train and Earth. Let's now say the person gets up out of her seat and walks toward the back of the train at $2\,\mathrm{m/s}$. This tells us she has a velocity relative to the reference frame of the train. Since the person is walking west, in the negative direction, we write her velocity with respect to the train as $\vec{v}_{\mathrm{PT}} = -2\,\mathrm{m/s}\,\hat{i}$. We can add the two velocity vectors to find the velocity of the person with respect to Earth. This relative velocity is written as

$$\vec{v}_{\mathrm{PE}} = \vec{v}_{\mathrm{PT}} + \vec{v}_{\mathrm{TE}}.$$

- **Relative Velocity in Two Dimensions Example:** Consider a particle P and reference frames S and S', The position of the origin of S' as measured in S is $\vec{r}_{S'S}$, the position of P as measured in S' is $\vec{r}_{PS'}$, and the position of P as measured in S is $\vec{r}_{PS}$.
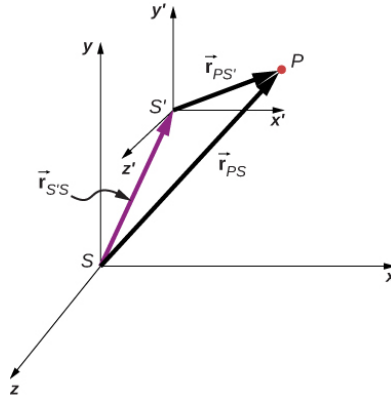
From this, we see

$$\vec{\mathbf{r}}_{PS} = \vec{\mathbf{r}}_{PS'} + \vec{\mathbf{r}}_{S'S}.$$

- **Relative velocities (Still using previous example)**: The relative velocities are the time derivatives of the position vectors. Therefore,

$$\vec{\mathbf{v}}_{PS} = \vec{\mathbf{v}}_{PS'} + \vec{\mathbf{v}}_{S'S}.$$

So we see the velocity of a particle relative to S is equal to its velocity relative to S' plus the velocity of S' relative to S

- **Relative accelerations (Still using same example)**: We can also see how the accelerations are related as observed in two reference frames by differentiating

$$\vec{\mathbf{a}}_{PS} = \vec{\mathbf{a}}_{PS'} + \vec{\mathbf{a}}_{S'S}.$$

We see that if the velocity of S' relative to S is a constant, then $\vec{a}_{S'S} = 0$ and

$$\vec{\mathbf{a}}_{PS} = \vec{\mathbf{a}}_{PS'}.$$

This says the acceleration of a particle is the same as measured by two observers moving at a constant velocity relative to each other.

- **Percent difference equation**: If A is the experimental value, and B is the actual value, then the percent difference is given by

$$\text{Percent difference } = \frac{|A - B|}{\frac{A+B}{2}} \cdot 100\%.$$

Calculus III

3.1   Chapter 1: Parametric equations and polar coordinates

3.1.1   Definitions and Theorems

- **Parametric equations, parameter**: If x and y are continuous functions of t on an interval I, then the equations

$$x = x(t) \quad \text{and} \quad y = y(t)$$

  are called **parametric equations** and t is called the **parameter**.

- **Parametric Curve**: The set of points (x, y) obtained as t varies over the interval I is called the graph of the parametric equations. The graph of parametric equations is called a **parametric curve** or plane curve, and is denoted by C.

- **Eliminating the parameter:** This allows us to rewrite the two equations as a single equation relating the variables x and y. Then we can apply any previous knowledge of equations of curves in the plane to identify the curve.

  - Solve one of the equations for t

  - Plug the equation for t into the equation still in terms of t

  - Sketch the curve on the interval I

- **Domain consideration when graphing by eliminating the parameter**: Suppose we have the equations

$$x = 2t^2$$
$$y = t^4 + 1.$$

  If we solve x for t, we get

$$t = \pm\sqrt{\frac{1}{2}x}.$$

  We see that the domain of t is restricted to $t \geqslant 0$, thus, the graph of this equation will only have the positive side.

- **Parameterizing a curve** is when we start with the equation of a curve and determine a pair of parametric equations for that curve.

  - To find the first Parameterization, Define $x(t) = t$ and $y(t)$ as the function given, with t instead of x

  - Verify there is no restriction on the domain of the original graph. Thus there is no restriction on the values of t

  - To find the second parameterization, choose some function for $x(t)$. Ensure that the domain is the set of all real numbers

  - Plug $x(t)$ into the original function and solve to get $y(t)$

- **Parametric equations for a cylcloid**

$$x(t) = a(t - \sin t), \quad y(t) = a(1 - \cos t).$$

- **The general parametric equations for a hypocycloid are:**

$$x(t) = (a - b)\ \cos t + b \cos\left(\frac{a - b}{b}\right) t$$

$$y(t) = (a - b)\ \sin t + b \sin\left(\frac{a - b}{b}\right) t$$

.

- **Derivatives of Parametric Equations**: Consider the plane curve defined by the parametric equations $x = x(t)$ and $y = y(t)$. Suppose that $x'(t)$ and $y'(t)$ exist, and assume that $x'(t) \neq 0$. Then the derivative $\frac{dy}{dx}$ is given by

$$\frac{dy}{dx} = \frac{\frac{dy}{dt}}{\frac{dx}{dt}} = \frac{y'(t)}{x'(t)}.$$

- **Second order derivatives of parametric functions**

$$\frac{d^2 y}{dx^2} = \frac{d}{dx}\left(\frac{dy}{dx}\right) = \frac{\left(\frac{d}{dt}\right)\left(\frac{dy}{dx}\right)}{\frac{dx}{dt}}.$$

- **Integral involving parametric equations** Consider the non-self-intersecting plane curve defined by the parametric equations

$$x = x(t), \quad y = y(t), \quad a \leqslant t \leqslant b$$

and assume that $x(t)$ is differentiable. The area under this curve is given by

$$A = \int_a^b y(t) x'(t)\, dt.$$

- **Arc Length of a Parametric Curve**: Consider the plane curve defined by the parametric equations

$$x = x(t), \quad y = y(t), \quad t_1 \leqslant t \leqslant t_2$$

and assume that $x(t)$ and $y(t)$ are differentiable functions of t. Then the arc length of this curve is given by

$$s = \int_{t_1}^{t_2} \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2}\, dt.$$

Or simply

$$s = \int_a^b \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\, dx.$$

- **Surface area for a parametric curve**: The analogous formula for a parametrically defined curve is

$$S = 2\pi \int_a^b y(t) \sqrt{(x'(t))^2 + (y'(t))^2}\, dt$$

provided that $y(t)$ is not negative on $[a, b]$.

- **Parametric equations for a circle (with $(h, k) = (0, 0)$)**

$$x(t) = r \cos(t)$$
$$y(t) = r \sin(t).$$

For $0 \leqslant t \leqslant 2\pi$

- **Parametric equations for the upper half of a semi-circle (with $(h,k) = (0,0)$)**

$$x(t) = r\cos(t)$$
$$y(t) = r\sin(t).$$

For $0 \leqslant t \leqslant \pi$

- **Parametric equations for the lower half of a semi-circle (with $(h,k) = (0,0)$)**

$$x(t) = r\cos(t)$$
$$y(t) = r\sin(t).$$

For $\pi \leqslant t \leqslant 2\pi$

- **Note: A graph has a horizontal tangent line when the derivative equals zero.**

- **Note: A graph has a vertical tangent line when the derivative does not exist**

- **Converting Points between Coordinate Systems**: Given a point P in the plane with Cartesian coordinates (x, y) and polar coordinates (r, θ), the following conversion formulas hold true:

$$x = r\cos\theta \quad \text{and} \quad y = r\sin\theta,.$$

$$r^2 = x^2 + y^2 \quad \text{and} \quad \tan\theta = \frac{y}{x}..$$

These formulas can be used to convert from rectangular to polar or from polar to rectangular coordinates.

- **Sometimes finding θ with the formula is not possible.** Consider the point $P(0,3)$, using the formula $\tan\theta = \frac{3}{0}$ is undefined. Instead, we graph the point $(0,3)$ and observe the angle between the x and y axis is $\frac{\pi}{2}$

- **The polar representation of a point is not unique.** Every point in the plane has an infinite number of representations in polar coordinates. However, each point in the plane has only one representation in the rectangular coordinate system.

- The line segment starting from the center of the graph going to the right (called the positive x-axis in the Cartesian system) is the **polar axis**.

- The center point is the **pole**, or origin, of the coordinate system, and corresponds to $r = 0$.

- **If the value of r is positive**, move that distance along the terminal ray of the angle. **If it is negative**, move along the ray that is opposite the terminal ray of the given angle.
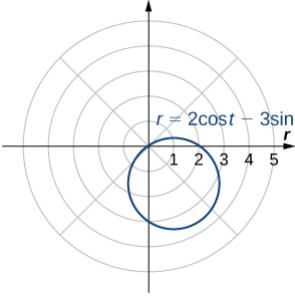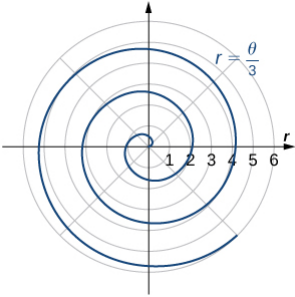
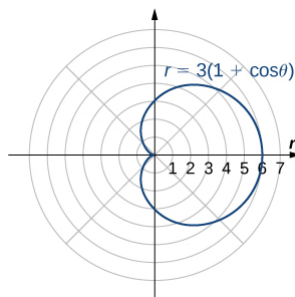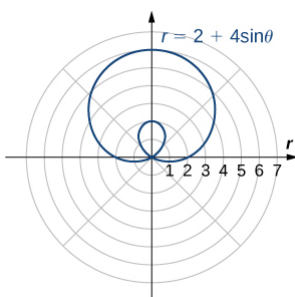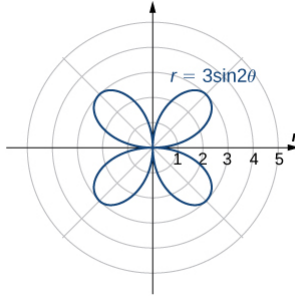- A **Polar equation** has the form
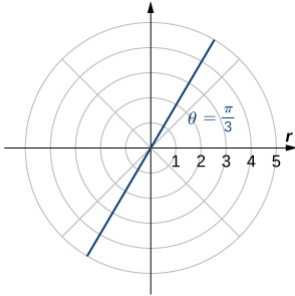
$$r = f(\theta).$$

- **Plotting a Curve in Polar Coordinates**

  1. Create a table with two columns. The first column is for θ, and the second column is for r.
  2. Create a list of values for θ.
  3. Calculate the corresponding r values for each θ.
  4. Plot each ordered pair (r, θ) on the coordinate axes.
  5. Connect the points and look for a pattern.

- **Types of polar curves**

Name	Equation	Example
Line passing through the pole with slope $\tan K$	$\theta = K$	
Circle	$r = a\cos\theta + b\sin\theta$	
Spiral	$r = a + b\theta$	

Name	Equation	Example
Cardioid	$r = a(1 + \cos\theta)$ $r = a(1 - \cos\theta)$ $r = a(1 + \sin\theta)$ $r = a(1 - \sin\theta)$	 $r = 3(1 + \cos\theta)$
Limacon	$r = a\cos\theta + b$ $r = a\sin\theta + b$	 $r = 2 + 4\sin\theta$
Rose	$r = a\cos(b\theta)$ $r = a\sin(b\theta)$	 $r = 3\sin 2\theta$

- For the rose, **If the coefficient of θ is even**, the graph has twice as many petals as the coefficient. **If the coefficient of θ is odd, then the number of petals equals the coefficient.**

- **Graphing a polar curve.**

  - Make graph in rectangular system (use θ as horizontal axis and r as vertical)
  - Translate over to polar
  - The circles represent values of r

- **Area of a Region Bounded by a Polar Curve**: Suppose f is continuous and nonnegative on the interval $\alpha \leqslant \theta \leqslant \beta$ with $0 < \beta - \alpha \leqslant 2\pi$. The area of the region bounded by the graph of $r = f(\theta)$ between the radial lines $\theta = \alpha$ and $\theta = \beta$ is

$$A = \frac{1}{2} \int_\alpha^\beta [f(\theta)]^2 \, d\theta = \frac{1}{2} \int_\alpha^\beta r^2 \, d\theta.$$

- **Area between two polar curves**:

$$A = \frac{1}{2} \int_\alpha^\beta f(\theta)^2 - g(\theta)^2 \, d\theta.$$

Where $f(\theta) \geqslant g(\theta) \forall \, \alpha \leqslant \theta \leqslant \beta$

- **Bounds of integration for area outside some curve and inside some curve**: We find the bounds of integration the same way we found them for regularo functions, we find the points of intersection by setting the two functions equal to each other

- **Arc Length of a Curve Defined by a Polar Function**: Let f be a function whose derivative is continuous on an interval $\alpha \leqslant \theta \leqslant \beta$. The length of the graph of $r = f(\theta)$ from $\theta = \alpha$ to $\theta = \beta$ is

$$L = \int_\alpha^\beta \sqrt{[f(\theta)]^2 + [f'(\theta)]^2} \, d\theta$$

$$= \int_\alpha^\beta \sqrt{r^2 + \left(\frac{dr}{d\theta}\right)^2} \, d\theta..$$

- **Absolute value bars**: Consider the integral

$$20 \int_0^{2\pi} \sqrt{\cos^2\left(\frac{\theta}{2}\right)} \, d\theta.$$

If we cancel out the sqrt and square, we must include absulute value bars. This is because $\cos\left(\frac{\theta}{2}\right)$ can be negative on the interval $[0, 2\pi]$. The integral becomes

$$20 \int_0^{2\pi} \left| \cos\left(\frac{\theta}{2}\right) \right| \, d\theta.$$

To solve this, we use symmetry to change the bounds. Because the graph of the polar curve $(10 + 10\cos\theta)$ is symmetric, we can integrate instead over the range $0, \pi$, and multiply the result by 2.

- **Derivative of polar equaotion**: Given some function $r = f(\theta)$. We can find the derivative with

$$\frac{dy}{dx} = \frac{\frac{dy}{d\theta}}{\frac{dx}{d\theta}} = \frac{\frac{dr}{d\theta}\sin\theta + r\cos\theta}{\frac{dr}{d\theta}\cos\theta - r\sin\theta}.$$

- **Find equation of tangent line given $r = f(\theta)$ and point θ.**

- Find r with given θ.
- Plug r into $x = r\cos\theta$, $y = r\sin\theta$ to get point $P(x, y)$
- Find $\frac{dy}{dx}$ of $r = f(\theta)$
- Plug in θ to get slope m
- Use point slope form to find equation

3.1.2 Problems to remember

- **Eliminating the parameter:** Sometimes it is necessary to be a bit creative in eliminating the parameter. The parametric equations for this example are

$$x(t) = 4\cos t, \quad y(t) = 3\sin t.$$

Solving either equation for t directly is not advisable because sine and cosine are not one-to-one functions. However, dividing the first equation by 4 and the second equation by 3 (and suppressing the t) gives us

$$\cos t = \frac{x}{4}, \quad \sin t = \frac{y}{3}.$$

Now use the Pythagorean identity $\cos^2 t + \sin^2 t = 1$ and replace the expressions for $\sin t$ and $\cos t$ with the equivalent expressions in terms of x and y. This gives

$$\left(\frac{x}{4}\right)^2 + \left(\frac{y}{3}\right)^2 = 1$$
$$\frac{x^2}{16} + \frac{y^2}{9} = 1.$$

This is the equation of a horizontal ellipse centered at the origin, with semimajor axis 4 and semiminor axis 3 as shown in the following graph.

- **Convert from cartesian to polar**: Consider the point $P(1,1)$. First we find r and θ

$$r^2 = x^2 + y^2$$
$$r = \sqrt{1^2 + 1^2}$$
$$r = \sqrt{2}$$
$$\tan\theta = \frac{y}{x} = \frac{1}{1}$$
$$\theta = \tan^{-1} 1$$
$$\theta = \frac{\pi}{4}.$$

Thus we have the point $\left(\sqrt{2}, \frac{\pi}{4}\right)$

- **Graphing a polar equation**: Graph the curve defined by the function $r = 4\sin\theta$. Identify the curve and rewrite the equation in rectangular coordinates.

Because the function is a multiple of a sine function, it is periodic with period 2π, so use values for θ between 0 and 2π

θ	$r = 4\sin\theta$	θ	$r = 4\sin\theta$
0	0	π	0
$\frac{\pi}{6}$	2	$\frac{7\pi}{6}$	-2
$\frac{\pi}{4}$	$2\sqrt{2} \approx 2.8$	$\frac{5\pi}{4}$	$-2\sqrt{2} \approx -2.8$
$\frac{\pi}{3}$	$2\sqrt{3} \approx 3.4$	$\frac{4\pi}{3}$	$-2\sqrt{3} \approx -3.4$
$\frac{\pi}{2}$	4	$\frac{3\pi}{2}$	-4
$\frac{2\pi}{3}$	$2\sqrt{3} \approx 3.4$	$\frac{5\pi}{3}$	$-2\sqrt{3} \approx -3.4$
$\frac{3\pi}{4}$	$2\sqrt{2} \approx 2.8$	$\frac{7\pi}{4}$	$-2\sqrt{2} \approx -2.8$
$\frac{5\pi}{6}$	2	$\frac{11\pi}{6}$	-2
2π	0		

Plotting these points gives the graph of a circle. The equation $r = 4\sin\theta$ can be converted into rectangular coordinates by first multiplying both sides by r. This gives the equation $r^2 = 4r\sin\theta$. Next use the facts that $r^2 = x^2 + y^2$ and $y = r\sin\theta$. This gives $x^2 + y^2 = 4y$. To put this equation into standard form, subtract $4y$ from both sides of the equation and complete the square:

$$x^2 + (y^2 - 4y) = x^2 + (y^2 - 4y + 4) = x^2 + (y-2)^2 = 0 + 4.$$

This is the equation of a circle with radius 2 and center $(0, 2)$ in the rectangular coordinate system.

- **Finding the Arc Length of a Polar Curve**:

$$Find the arc length of the polar curve\ r = 2 + 2\cos\theta.$$

When $\theta = 0$, $r = 2 + 2\cos(0) = 4$. Furthermore, as θ goes from 0 to 2π, the cardioid is traced out exactly once. Therefore, these are the limits of integration. Using $f(\theta) = 2 + 2\cos(\theta)$, $\alpha = 0$, and $\beta = 2\pi$. Thus we have

$$
\begin{aligned}
L &= \int_\alpha^\beta \sqrt{[f(\theta)]^2 + [f'(\theta)]^2}\, d\theta \\
&= \int_0^{2\pi} \sqrt{[2 + 2\cos(\theta)]^2 + [-2\sin(\theta)]^2}\, d\theta \\
&= \int_0^{2\pi} \sqrt{4 + 8\cos(\theta) + 4\cos^2(\theta) + 4\sin^2(\theta)}\, d\theta \\
&= \int_0^{2\pi} \sqrt{4 + 8\cos(\theta) + 4(\cos^2(\theta) + \sin^2(\theta))}\, d\theta \\
&= \int_0^{2\pi} \sqrt{8 + 8\cos(\theta)}\, d\theta \\
&= 2\int_0^{2\pi} \sqrt{2 + 2\cos(\theta)}\, d\theta..
\end{aligned}
$$

Next, using the identity $\cos(2\alpha) = 2\cos^2(\alpha) - 1$, add 1 to both sides and multiply by 2. This gives $2 + 2\cos(2\alpha) = 4\cos^2(\alpha)$. Substituting $\alpha = \frac{\theta}{2}$ gives $2 + 2\cos(\theta) = 4\cos^2\left(\frac{\theta}{2}\right)$, so the integral becomes

$$
\begin{aligned}
L &= 2\int_0^{2\pi} \sqrt{2 + 2\cos(\theta)}\, d\theta \\
&= 2\int_0^{2\pi} \sqrt{4\cos^2\left(\frac{\theta}{2}\right)}\, d\theta \\
&= 2\int_0^{2\pi} 2\left|\cos\left(\frac{\theta}{2}\right)\right|\, d\theta..
\end{aligned}
$$

The absolute value is necessary because the cosine is negative for some values in its domain. To resolve this issue, change the limits from 0 to π and double the answer. This strategy works because cosine is positive between 0 and $\frac{\pi}{2}$. Thus,

$$
\begin{aligned}
L &= 4\int_0^{2\pi} \left|\cos\left(\frac{\theta}{2}\right)\right|\, d\theta \\
&= 8\int_0^{\pi} \cos\left(\frac{\theta}{2}\right)\, d\theta \\
&= 8\left[2\sin\left(\frac{\theta}{2}\right)\right]_0^{\pi} \\
&= 16..
\end{aligned}
$$

3.2 Chapter 2: Vectors in Space

3.2.1 Definitions and Theorems

- The endpoints of the segment are called the **initial point** and the **terminal point** of the vector.

- The length of the line segment represents its magnitude. We use the notation $\|\vec{v}\|$ to denote the magnitude of the vector $\vec{v}$.

- A vector with an initial point and terminal point that are the same is called the **zero vector**, denoted $\vec{0}$.

- Vectors with the same magnitude and direction are called **equivalent vectors**. We treat equivalent vectors as equal, even if they have different initial points. Thus, if $\vec{v}$ and $\vec{w}$ are equivalent, we write

$$\vec{v} = \vec{w}.$$

- **Scalar Multiplication**: The product $k\vec{v}$ of a vector $\vec{v}$ and a scalar k is a vector with a magnitude that is $|k|$ times the magnitude of $\vec{v}$, and with a direction that is the same as the direction of $\vec{v}$ if $k > 0$, and opposite the direction of $\vec{v}$ if $k < 0$. This is called scalar multiplication. If $k = 0$ or $\vec{v} = \vec{0}$, then $k\vec{v} = \vec{0}$.

- **Vector Addition**: The sum of two vectors $\vec{v}$ and $\vec{w}$ can be constructed graphically by placing the initial point of $\vec{w}$ at the terminal point of $\vec{v}$. Then, the vector sum, $\vec{v} + \vec{w}$, is the vector with an initial point that coincides with the initial point of $\vec{v}$ and has a terminal point that coincides with the terminal point of $\vec{w}$. This operation is known as vector addition.
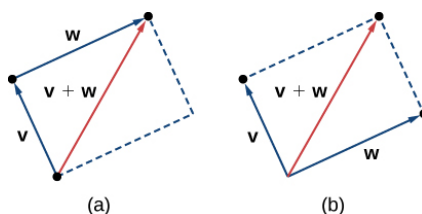
- **Vector difference**: We define $\vec{v} - \vec{w}$ as $\vec{v} + (-\vec{w}) = \vec{v} + (-1)\vec{w}$. The vector $\vec{v} - \vec{w}$ is called the vector difference. Graphically, the vector $\vec{v} - \vec{w}$ is depicted by drawing a vector from the terminal point of $\vec{w}$ to the terminal point of $\vec{v}$.
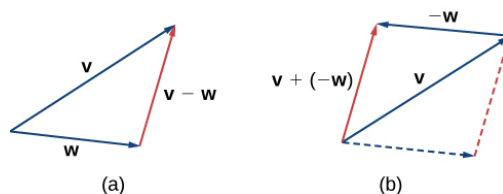
- **Triangle inequality**: the length of any one side is less than the sum of the lengths of the remaining sides. So we have

$$\|\vec{v} + \vec{w}\| \leqslant \|\vec{v}\| + \|\vec{w}\|.$$

- We call a vector with its initial point at the origin a **standard-position** vector.

- **Component form of a vector**: The vector with initial point $(0,0)$ and terminal point (x, y) can be written in component form as

$$\vec{v} = \langle x, y \rangle.$$

The scalars x and y are called the components of **v**.

- If a vector is in standard position, and its components are the same as the terminal point

- **Component form of a vector not in standard position**: Let $\vec{v}$ be a vector with initial point (x_i, y_i) and terminal point (x_t, y_t). Then we can express $\vec{v}$ in component form as $\vec{v} = \langle x_t - x_i, y_t - y_i \rangle$.

- **Magnitude of vector**: If a vector is given by components $\langle x, y \rangle$. Then this is the vector with initial point at the orgin $(0,0)$, and terminal point at (x,y). We find the magnitude of the vector with

$$\|\vec{v}\| = \sqrt{x^2 + y^2}.$$

If the vector is not in standard position, and we have initial point (x_1, x_2) and terminal point (x_2, y_2), then we find the magnitude with

$$\|\vec{v}\| = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}.$$

- **Scalar multiplication, and vector addition (component form)** Let $\mathbf{v} = \langle x_1, y_1 \rangle$ and $\mathbf{w} = \langle x_2, y_2 \rangle$ be vectors, and let k be a scalar.

Scalar multiplication: $k\mathbf{v} = \langle kx_1, ky_1 \rangle$

Vector addition: $\mathbf{v} + \mathbf{w} = \langle x_1, y_1 \rangle + \langle x_2, y_2 \rangle = \langle x_1 + x_2, y_1 + y_2 \rangle.$

- **Properties of Vector Operations**: Let **u**, **v**, and **w** be vectors in a plane. Let r and s be scalars.

1. $\mathbf{u} + \mathbf{v} = \mathbf{v} + \mathbf{u}$ (Commutative property)
2. $(\mathbf{u} + \mathbf{v}) + \mathbf{w} = \mathbf{u} + (\mathbf{v} + \mathbf{w})$ (Associative property)
3. $\mathbf{u} + \mathbf{0} = \mathbf{u}$ (Additive identity property)
4. $\mathbf{u} + (-\mathbf{u}) = \mathbf{0}$ (Additive inverse property)
5. $r(s\mathbf{u}) = (rs)\mathbf{u}$ (Associativity of scalar multiplication)
6. $(r + s)\mathbf{u} = r\mathbf{u} + s\mathbf{u}$ (Distributive property)
7. $r(\mathbf{u} + \mathbf{v}) = r\mathbf{u} + r\mathbf{v}$ (Distributive property)
8. $1\mathbf{u} = \mathbf{u}, \quad 0\mathbf{u} = \mathbf{0}$ (Identity and zero properties)

Note $CAAA^{-1}(ASM)D^2(I\&Z)$

- **Finding components of a vector given the magnitude and the angle θ**

$$x = \|\vec{v}\| \cos \theta$$
$$y = \|\vec{v}\| \sin \theta.$$

- **Unit vector**: A unit vector is a vector with magnitude 1. For any nonzero vector $\vec{v}$, we can use scalar multiplication to find a unit vector $\vec{u}$ that has the same direction as $\vec{v}$. To do this, we multiply the vector by the reciprocal of its magnitude:

$$\vec{u} = \frac{1}{\|\vec{v}\|} \vec{v}.$$

- **xy-plane**:

$$\{(x, y, 0) \ : \ x, y \in \mathbb{R}\}.$$

Described by the equation $z = 0$

- **xz-plane**

$$\{(x, 0, z) \ : \ x, z \in \mathbb{R}\}.$$

Described by the equation $y = 0$

- **yz-plane**

$$\{(0, y, z) \ : \ y, z \in \mathbb{R}\}.$$

Described by the equation $x = 0$

- the coordinate planes divide space between them into eight regions about the origin, called **octants**. The octants fill $\mathbb{R}^3$ the same way that quadrants fill $\mathbb{R}^2$,

- **Distance formula for three-dimensional space**: The distance d between points (x_1, y_1, z_1) and (x_2, y_2, z_2) is given by the formula

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}.$$

- **Equations of planes parallel to coordinate planes**

   1. The plane in space that is parallel to the xy-plane and contains point (a,b,c) can be represented by the equation $z = c$.

   2. The plane in space that is parallel to the xz-plane and contains point (a,b,c) can be represented by the equation $y = b$.

   3. The plane in space that is parallel to the yz-plane and contains point (a,b,c) can be represented by the equation $x = a$

- A **sphere** is the set of all points in space equidistant from a fixed point, the center of the sphere, just as the set of all points in a plane that are equidistant from the center represents a circle. In a sphere, as in a circle, the distance from the center to a point on the sphere is called the *radius*.

- **Standard equation of a sphere**: The sphere with center (a, b, c) and radius r can be represented by the equation

$$(x - a)^2 + (y - b)^2 + (z - c)^2 = r^2.$$

This equation is known as the **standard equation of a sphere**.

- **Properties of vectors in space**: Let $\vec{v} = \langle x_1, y_1, z_1 \rangle$ and $\vec{w} = \langle x_2, y_2, z_2 \rangle$ be vectors, and let k be a scalar.

   - Scalar multiplication:

$$k\vec{v} = \langle kx_1, ky_1, kz_1 \rangle.$$

   - Vector addition:

$$\vec{v} + \vec{w} = \langle x_1, y_1, z_1 \rangle + \langle x_2, y_2, z_2 \rangle = \langle x_1 + x_2, y_1 + y_2, z_1 + z_2 \rangle.$$

    – Vector subtraction:

$$\vec{v} - \vec{w} = \langle x_1, y_1, z_1 \rangle - \langle x_2, y_2, z_2 \rangle = \langle x_1 - x_2, y_1 - y_2, z_1 - z_2 \rangle.$$

    – Vector magnitude:

$$\|\vec{v}\| = \sqrt{x_1^2 + y_1^2 + z_1^2}.$$

    – Unit vector in the direction of $\vec{v}$:

$$\frac{1}{\|\vec{v}\|}\vec{v} = \frac{1}{\|\vec{v}\|}\langle x_1, y_1, z_1 \rangle$$
$$= \left\langle \frac{x_1}{\|\vec{v}\|}, \frac{y_1}{\|\vec{v}\|}, \frac{z_1}{\|\vec{v}\|} \right\rangle, \text{ if } \vec{v} \neq 0.$$

- **The dot product**: The dot product of vectors $\vec{u} = \langle u_1, u_2, u_3 \rangle$ and $\vec{v} = \langle v_1, v_2, v_3 \rangle$ is given by the sum of the products of the components

$$\vec{u} \cdot \vec{v} = u_1 v_1 + u_2 v_2 + u_3 v_3.$$

The dot product **does not** return a new vector, the result is a **scalar**

- **Properties of the dot product** Let $\vec{u}$, $\vec{v}$, and $\vec{w}$ be vectors, and let c be a scalar.

  1. Commutative property: $\vec{u} \cdot \vec{v} = \vec{v} \cdot \vec{u}$
  2. Distributive property: $\vec{u} \cdot (\vec{v} + \vec{w}) = \vec{u} \cdot \vec{v} + \vec{u} \cdot \vec{w}$
  3. Associative property of scalar multiplication: $(c\vec{u} \cdot \vec{v}) = (c\vec{u}) \cdot \vec{v} = \vec{u} \cdot (c\vec{v})$
  4. Property of magnitude: $\vec{v} \cdot \vec{v} = \|\vec{v}\|^2$

- **Evaluating a dot product**: The dot product of two vectors is the product of the magnitude of each vector and the cosine of the angle between them:

$$\vec{u} \cdot \vec{v} = \|\vec{u}\| \cdot \|\vec{v}\| \cdot \cos\theta.$$

- **Find the measure of the angle between two nonzero vectors**:

$$\cos\theta = \frac{\vec{u} \cdot \vec{v}}{\|\vec{u}\|\|\vec{v}\|}.$$

Note: We are considering $0 \leqslant \theta \leqslant \pi$

- **Vector Projection**: The vector projection of **v** onto **u** has the same initial point as **u** and **v** and the same direction as **u**, and represents the component of **v** that acts in the direction of **u**.

$$\mathrm{proj}_{\vec{u}}\vec{v} = \frac{\vec{v} \cdot \vec{u}}{\|\vec{u}\|^2}\vec{u}.$$

We say "The vector projection of $\vec{v}$ onto $\vec{u}$"

- **Scalar projection notation**: This is the length of the vector projection and is denoted

$$\|\mathrm{proj}_{\vec{u}}\vec{v}\| = \mathrm{comp}_{\vec{u}}\vec{v} = \frac{\vec{u} \cdot \vec{v}}{\|\vec{u}\|}.$$

- **Decompose some vector $\vec{v}$ into orthogonal components such that one of the component vectors has the same direction as $\vec{u}$**

  - First, we compute $\vec{p} = \text{proj}_{\vec{u}} \vec{v}$
  - Then, we define $\vec{q} = \vec{v} - \vec{p}$
  - Check that $\vec{q}$ and $\vec{p}$ are orthogonal by finding $\vec{q} \cdot \vec{p}$

- **Work**: When a constant force is applied to an object so the object moves in a straight line from point P to point Q, the work W done by the force $\mathbf{F}$, acting at an angle θ from the line of motion, is given by

$$W = \vec{F} \cdot \overrightarrow{PQ} = \|\vec{F}\| \|\overrightarrow{PQ}\| \cos\theta.$$

- **Two vectors are orthogonal if**

$$\vec{u} \cdot \vec{v} = 0.$$

- **Two vectors are parallel if**

$$\exists \alpha \text{ s.t } \alpha \vec{u} = \vec{v}.$$

- **Scalar projection componets of a vector**

$$\vec{v} = \langle \text{comp}_{\hat{i}} \vec{v}, \text{comp}_{\hat{j}} \vec{v}, \text{comp}_{\hat{k}} \vec{v} \rangle.$$

- **Find direction angles for some vector**: Suppose we have some vector $\vec{v}$, to find the direction angles, we use the formula

$$\cos\theta = \frac{\vec{v} \cdot \vec{u}}{\|\vec{v}\| \|\vec{u}\|}.$$

  With the unit vectors $\hat{i}, \hat{j}, \hat{k}$. This will gives angles $\alpha, \ \beta, \ \gamma$

- **The Cross Product**: Let $\mathbf{u} = \langle u_1, u_2, u_3 \rangle$ and $\mathbf{v} = \langle v_1, v_2, v_3 \rangle$. Then, the cross product $\mathbf{u} \times \mathbf{v}$ is vector

$$\mathbf{u} \times \mathbf{v} = (u_2 v_3 - u_3 v_2)\mathbf{i} - (u_1 v_3 - u_3 v_1)\mathbf{j} + (u_1 v_2 - u_2 v_1)\mathbf{k}$$
$$= \langle u_2 v_3 - u_3 v_2, -(u_1 v_3 - u_3 v_1), u_1 v_2 - u_2 v_1 \rangle..$$

  Note: The cross product only works in $\mathbb{R}^3$, additionally, we measure the angle between $\vec{u}$ and $\vec{v}$ in $\vec{u} \times \vec{v}$ from $\vec{u}$ to $\vec{v}$

- **Cross product using matrix and discriminant**, suppose we have vectors $\vec{u}$ und $\vec{v}$. Then we can express them in matrix form as

$$\vec{u} \times \vec{v} = \begin{bmatrix} \hat{i} & \hat{j} & \hat{k} \\ u_x & u_y & u_z \\ v_x & v_y & v_z \end{bmatrix}.$$

  Then we can find the discriminant of this matrix to compute the cross product

$$\vec{u} \times \vec{v} = (u_y v_z - u_z v_y)\hat{i} - (u_x v_z - u_z v_x)\hat{k} + (u_x v_y - u_y v_x)\hat{j}.$$

- **Right hand rule for cross product**: The direction of $\mathbf{u} \times \mathbf{v}$ is given by the right-hand rule. If we hold the right hand out with the fingers pointing in the direction of $\mathbf{u}$, then curl the fingers toward vector $\mathbf{v}$, the thumb points in the direction of the cross product, as shown.
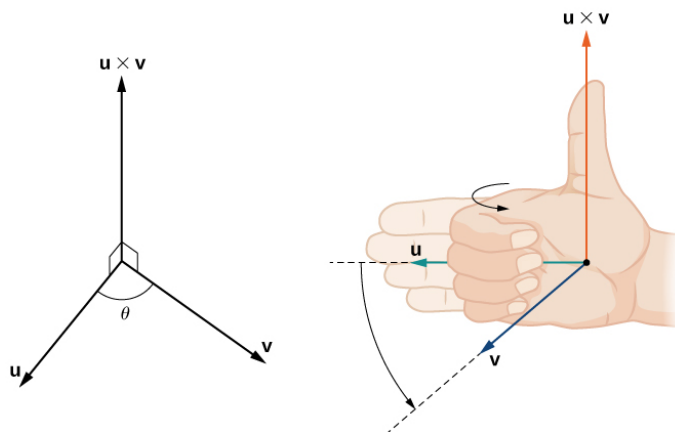
- **Properties of the Cross Product** Let $\mathbf{u}$, $\mathbf{v}$, and $\mathbf{w}$ be vectors in space, and let c be a scalar.

  1. Anticommutative property: $\mathbf{u} \times \mathbf{v} = -(\mathbf{v} \times \mathbf{u})$
  2. Distributive property: $\mathbf{u} \times (\mathbf{v} + \mathbf{w}) = \mathbf{u} \times \mathbf{v} + \mathbf{u} \times \mathbf{w}$
  3. Multiplication by a constant: $c(\mathbf{u} \times \mathbf{v}) = (c\mathbf{u}) \times \mathbf{v} = \mathbf{u} \times (c\mathbf{v})$
  4. Cross product of the zero vector: $\mathbf{u} \times \mathbf{0} = \mathbf{0} \times \mathbf{u} = \mathbf{0}$
  5. Cross product of a vector with itself: $\mathbf{v} \times \mathbf{v} = \mathbf{0}$
  6. Scalar triple product: $\mathbf{u} \cdot (\mathbf{v} \times \mathbf{w}) = (\mathbf{u} \times \mathbf{v}) \cdot \mathbf{w}$

- **Magnitude of the Cross Product**: Let $\mathbf{u}$ and $\mathbf{v}$ be vectors, and let θ be the angle between them. Then, $\|\mathbf{u} \times \mathbf{v}\| = \|\mathbf{u}\| \cdot \|\mathbf{v}\| \cdot \sin\theta$.

- **Applications of the cross product**:

  - Finding a vector orthogonal to two given vectors
  - Computing areas of triangles and parallelograms
  - Determining the volume of the three-dimensional geometric shape made of parallelograms known as a parallelepiped:w

- **Area of a Parallelogram** If we locate vectors $\mathbf{u}$ and $\mathbf{v}$ such that they form adjacent sides of a parallelogram, then the area of the parallelogram is given by $\|\mathbf{u} \times \mathbf{v}\|$.

- **Triple Scalar Product**:

  The triple scalar product of vectors $\mathbf{u}$, $\mathbf{v}$, and $\mathbf{w}$ is $\mathbf{u} \cdot (\mathbf{v} \times \mathbf{w})$.

  The triple scalar product is the determinant of the 3×3 matrix formed by the components of the vectors

- **triple scalar product identities**:

  (a) $\mathbf{u} \cdot (\mathbf{v} \times \mathbf{w}) = -\mathbf{u} \cdot (\mathbf{w} \times \mathbf{v})$
  (b) $\mathbf{u} \cdot (\mathbf{v} \times \mathbf{w}) = \mathbf{v} \cdot (\mathbf{w} \times \mathbf{u} = \mathbf{w} \cdot (\mathbf{u} \times \mathbf{v}))$

- **parallelepiped**: Let **u** and **v** be two vectors in standard position. If **u** and **v** are not scalar multiples of each other, then these vectors form adjacent sides of a parallelogram.

  Now suppose we add a third vector **w** that does not lie in the same plane as **u** and **v** but still shares the same initial point. Then these vectors form three edges of a parallelepiped, a three-dimensional prism with six faces that are each parallelograms,

- **Volume of a Parallelepiped**: The volume of a parallelepiped with adjacent edges given by the vectors **u**, **u**, and **w** is the absolute value of the triple scalar product:

$$V = \left| \mathbf{u} \cdot (\mathbf{v} \times \mathbf{w}) \right|.$$

- **Torque**: Measures the tendency of a force to produce rotation about an axis of rotation. Let **r** be a vector with an initial point located on the axis of rotation and with a terminal point located at the point where the force is applied, and let vector **F** represent the force. Then torque is equal to the cross product of **r** and **F**:

$$\tau = \mathbf{r} \times \mathbf{F}.$$

- **Choosing α to make parallel vectors equal**: Suppose we have two vectors **u** and **v**, and $\exists\, \alpha \in \mathbb{R}$ s.t $\alpha \mathbf{v} = \mathbf{u}$. Then

$$\alpha = \frac{\|\mathbf{u}\|}{\|\mathbf{v}\|}.$$

  Or if they are **anti-parallel**

$$\alpha = -\frac{\|\mathbf{u}\|}{\|\mathbf{v}\|}.$$

- **The zero vector is considered to be parallel to all vectors**

- **vector equation of a line**

$$\mathbf{r} = \mathbf{r}_0 + t\mathbf{v}.$$

  Where **v** is the direction vector (vector parallel to the line), t is some scalar, and **r**, $\mathbf{r}_0$ are position vectors

- **Parametric and Symmetric Equations of a Line**: A line L parallel to vector $\mathbf{v} = \langle a, b, c \rangle$ and passing through point $P(x_0, y_0, z_0)$ can be described by the following parametric equations:

$$x = x_0 + ta, \quad y = y_0 + tb, \quad \text{and} \quad z = z_0 + tc.$$

  If the constants a, b, and c are all nonzero, then L can be described by the symmetric equation of the line:
$$\frac{x - x_0}{a} = \frac{y - y_0}{b} = \frac{z - z_0}{c}.$$

  Note: The parametric equations of a line are not unique. Using a different parallel vector or a different point on the line leads to a different, equivalent representation. Each set of parametric equations leads to a related set of symmetric equations, so it follows that a symmetric equation of a line is not unique either.

- **Vector equation of a line reworked**: Suppose we have some line, with points $P(x_0, y_0, z_0)$, $Q(x_1, y_1, z_1)$. Where $\mathbf{p} = \langle x_0, y_0, z_0 \rangle$ and $\mathbf{Q} = \langle x_1, y_1, z_1 \rangle$ are the corresponding position vectors. Suppose we also have $\mathbf{r} = \langle x, y, z \rangle$. Then our vector equation for a line becomes

$$\mathbf{r} = \mathbf{p} + t\left(\vec{PQ}\right).$$

  By properties of vectors, we get the vector equation of a line passing through points P and Q to be

$$\mathbf{r} = (1-t)\mathbf{p} + t\mathbf{q}.$$

- **Equation of a line segment between two points P and Q**: Using the result from the previous item, we find the vector equation of the line segment between P and Q is

$$\mathbf{r} = (1-t)\mathbf{p} + t\mathbf{q}, \quad 0 \leqslant t \leqslant 1.$$

  Because when $t = 0$, $\mathbf{r} = \mathbf{p}$. When $t = 1$, $\mathbf{r} = \mathbf{q}$

- **parametric equations for this line segment**

$$\begin{cases} x = x_0 + t(x_1 - x_0) \\ y = y_0 + t(y_1 - y_0) \\ z = z_0 + t(z_1 - z_0) \end{cases} \tag{24}$$

  For $0 \leqslant t \leqslant 1$

- **Distance from a Point to a Line**: Let L be a line in space passing through point P with direction vector $\mathbf{v}$. If M is any point not on L, then the distance from M to L is

$$d = \frac{\left\|\vec{PM} \times \mathbf{v}\right\|}{\|\mathbf{v}\|}$$

- If two lines in space are not parallel, but do not intersect, then the lines are said to be **skew** lines

- **Classifying lines in space**

- **Testing for parallel, intersecting, or skew**: Suppose we have two sets of parametric equations for two lines.

– First we test for parallel lines, We find their direction vectors, if their direction vectors are parallel, the lines are parallel.

– If they are not parallel, we can test for intersection. This is best explained with an example

Suppose we have the equations

$$L_1: \quad x = 3 + 2t \quad y = 4 - t \quad z = 1 + 3t$$
$$L_2: \quad x = 1 + 4s \quad y = 3 - 2s \quad z = 4 + 5s.$$

First, we equate each set of equations

$$3 + 2t = 1 + 4s$$
$$4 - t = 3 - 2s$$
$$1 + 3t = 4 + 5s.$$

Next, we solve the first equation for one of the variables, in this case we choose to solve for t

$$t = 2s - 1.$$

Now, we want to plug this into the second equation. This gives

$$4 - (2s - 1) = 3 - 2s$$
$$2 = 0.$$

Since we this statement is not true, we know the lines must not be intersecting. In this case, we know they must be skew

However, suppose we got some value for s, such as $s = 1$, we can then plug this value into the equation we got for t ($t = 2s - 1$) to get a value for t, after we have a value for t, we can plug both s and t into the third equation and evaluate the truthiness of its outcome. If the outcome is true, we have a valid solution for the system of equations.

Note: If the lines are known to be skew, then we compute the dot product of their direction angles to check for orthogonality.

- given any three points that do not all lie on the same line, there is a unique **plane** that passes through these points. Just as a line is determined by two points, **a plane is determined by three.**

- given two distinct, intersecting lines, **there is exactly one plane containing both lines.**

- A plane is also **determined by a line and any point that does not lie on the line.**

- We say that $\mathbf{n}$ is a normal vector, or perpendicular to the plane.

- **Vector equation of a plane**: Given a point P and vector $\mathbf{n}$, the set of all points Q satisfying the equation $\mathbf{n} \cdot \overrightarrow{PQ} = 0$ forms a plane. The equation

$$\mathbf{n} \cdot \overrightarrow{PQ} = 0$$

is known as the vector equation of a plane.

- **Scalar equation of a plane**: The scalar equation of a plane containing point $P = (x_0, y_0, z_0)$ with normal vector $\mathbf{n} = \langle a, b, c \rangle$ is

$$a(x - x_0) + b(y - y_0) + c(z - z_0) = 0.$$

- **General form of the equation of a plane**: This equation (the one above) can be expressed as $ax + by + cz + d = 0$, where $d = -ax_0 - by_0 - cz_0$. This form of the equation is sometimes called the general form of the equation of a plane.

- any three points that do not all lie on the same line determine a plane. Given three such points, we can find an equation for the plane containing these points.

- **The Distance between a Plane and a Point**: Suppose a plane with normal vector $\mathbf{n}$ passes through point Q. The distance d from the plane to a point P not in the plane is given by

$$d = \|\text{proj}_{\mathbf{n}} \vec{QP}\| = \left| \text{comp}_{\mathbf{n}} \vec{QP} \right| = \frac{\left| \vec{QP} \cdot \mathbf{n} \right|}{\|\mathbf{n}\|}.$$

- For two planes in space, we have only two possible relationships: **The two distinct planes are parallel or they intersect. When two planes are parallel, their normal vectors are parallel. When two planes intersect, the intersection is a line**

- **Finding line of intersection for two planes**: Suppose we are given the parametric equations for two planes

  - Check if their normals are parallel, if not, we know the planes must intersect
  - Find a common point that satisfies both equations (perhaps the origin)
  - Eliminate one of the variables (perhaps by adding them)
  - After elimination we should have one variable equal to one of the others, we then plug this into one of the equations to get two variables in terms of the third.
  - Define this third variable in terms of t to get x, y, z in terms of t, these equations will be the paramteric equations for the line of intersection

- **find the angle formed by the intersection of two planes:** We can use normal vectors to calculate the angle between the two planes.

We can find the measure of the angle θ between two intersecting planes by first finding the cosine of the angle, using the following equation:

$$\cos \theta = \frac{\left| \mathbf{n}_1 \cdot \mathbf{n}_2 \right|}{\|\mathbf{n}_1\| \|\mathbf{n}_2\|}.$$

We can then use the angle to determine whether two planes are parallel or orthogonal or if they intersect at some other angle.

- **Finding the distance between two parallel planes**: Let $P(x_0, y_0, z_0)$ be a point. The distance from P to plane $ax + by + cz + k = 0$ is given by

$$d = \frac{|ax_0 + by_0 + cz_0 + k|}{\sqrt{a^2 + b^2 + c^2}}.$$

- **Find the intersection of a plane with a line**:

  - First, we get the line in parametric form, with t is the parameter.
  - When then plug our parametric equations into the corresponding plane equation variables
  - Solve for t,
  - Plug t into parametric equation to get point (x, y, z)

$$53 = 15m/s(1.5s) + \frac{1}{2}a(1.5s)^2$$
$$a = 27m/s^2.$$

- **Conic sections, The parabola**: A parabola is the set of all points in a plane equidistant from a fixed point F (the focus) and a fixed line ℓ (the directrix) that lie in the plane.

- **Parabola that opens up**: Given a parabola opening upward with vertex located at (h, k) and focus located at $(h, k + p)$, where p is a constant, the equation for the parabola is given by

$$y = \frac{1}{4p}(x - h)^2 + k$$

Vertex: (h, k)

Focus: $(h, k + p)$

Directrix $y = k - p$

AOS $x = h$.

This is the **standard form** of a parabola.
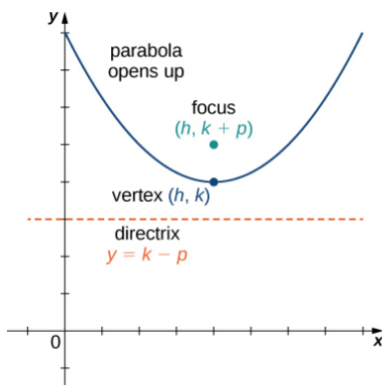
- **Parabola that opens down**:

$$y = -\frac{1}{4p}(x - h)^2 + k$$

Vertex: (h, k)

Focus: $(h, k - p)$

Directrix $y = k + p$

AOS $x = h$.
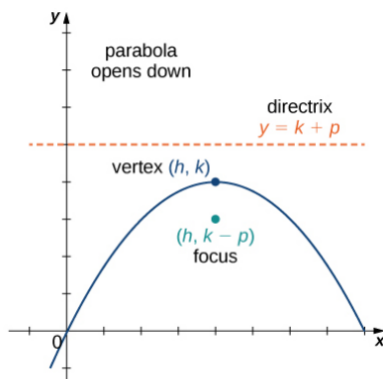
- **Parabola opens right**:

$$x = \frac{1}{4p}(y - k)^2 + h$$

Vertex: (h, k)

Focus: $(h + p, k)$

Directrix $x = h - p$
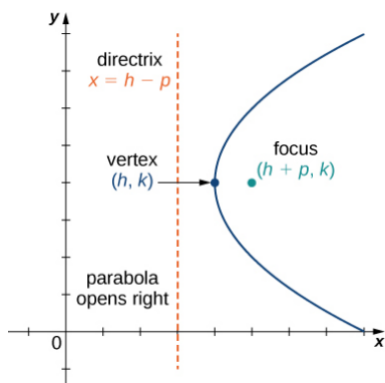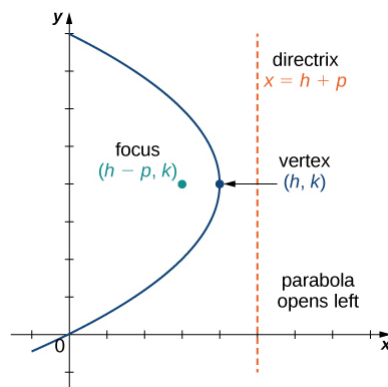
AOS $y = k$.

- **Parabola opens left**:

$$x = -\frac{1}{4p}(y-k)^2 + h$$

Vertex: (h, k)

Focus: $(h - p, k)$

Directrix $x = h + p$

AOS $y = k$.

- **Genaral form of a parabola**: The equation of a parabola can be written in the general form, though in this form the values of h, k, and p are not immediately recognizable. The general form of a parabola is written as

$$ax^2 + bx + c = 0 \quad \text{or} \quad ay^2 + bx + c = 0.$$

Note: The first equation represents a parabola that opens either up or down. The second equation represents a parabola that opens either to the left or to the right. To put the equation into standard form, use the method of completing the square.

- **Conic sections, The ellipse**: An ellipse is the set of all points for which the sum of their distances from two fixed points (the foci) is constant.
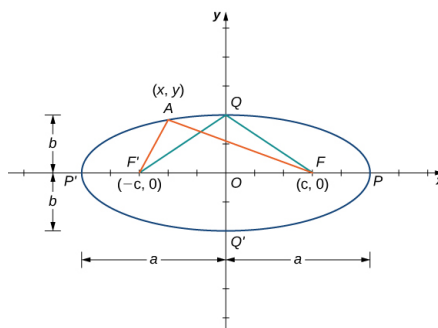
Foci: There are two foci

Directrices: There are two directrices (plural of directrix)

Major axis: An ellipse has two axis, one short and one long. The major axis is the longer of the two and has length $2a$

Minor axis: The shorter axis has length $2b$

Finding c with a and b, to find c, we use

$$c^2 = a^2 - b^2.$$

- **Ellipse with horizontal major axis**: This type of ellipse has the form

$$\frac{(x-h)^2}{a^2} + \frac{(y-k)^2}{b^2} = 1$$

$$\text{Center } (h, k)$$

$$\text{Foci: } (h \pm c, k)$$

$$\text{Directrices: } x = h \pm \frac{a^2}{c}.$$

- **Ellipse with vertical major axis:** This type of ellipse has the form

$$\frac{(x-h)^2}{b^2} + \frac{(y-k)^2}{a^2} = 1$$

$$\text{Center: } (h, k)$$

$$\text{Foci: } (h, k \pm c)$$

$$\text{Directrices: } y = k \pm \frac{a^2}{c}.$$

- **General form of an ellipse**: The equation of an ellipse is in general form if it is in the form

$$Ax^2 + By^2 + Cx + Dy + E = 0.$$

where A and B are either both positive or both negative. To convert the equation from general to standard form, use the method of completing the square.

- **Conic sections, the Hyperbola**: A hyperbola is the set of all points where the difference between their distances from two fixed points (the foci) is constant.
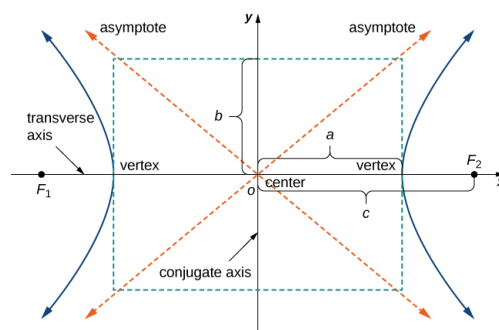
Foci: There are two foci

Directrices: There are two directrices (plural of directrix)

Asymptotes: There are two Asymptotes

Tranverse axis (major axis) has length $2a$

Conjugate axis (minor axis) has length $2b$

Finding c **with** a **and** b, to find c, we use

$$c^2 = a^2 + b^2.$$

- **Hyperbola opening left and right (horizontal major axis)**

$$\frac{(x-h)^2}{a^2} - \frac{(y-k)^2}{b^2} = 1$$

Center: (h, k) Foci: $(h \pm c, k)$

Asymptotes: $y = k \pm \dfrac{b}{a}(x - h)$

Directrices: $x = h \pm \dfrac{a^2}{c}.$

- **Hyperbola opening up and down (vertical major axis)**

$$\frac{(y-k)^2}{a^2} - \frac{(x-h)}{b^2} = 1$$

Center: (h, k) Foci: $(h, k \pm c)$

Asymptotes: $y = k \pm \dfrac{a}{b}(x - h)$

Directrices: $y = k \pm \dfrac{a^2}{c}.$

- **Hyperbola general form**: The equation of a hyperbola is in general form if it is in the form

$$Ax^2 + By^2 + Cx + Dy + E = 0.$$

where A and B have opposite signs. In order to convert the equation from general to standard form, use the method of completing the square.

- **Eccentricity and directrix of conic sections**: The eccentricity e of a conic section is defined to be the distance from any point on the conic section to its focus, divided by the perpendicular distance from that point to the nearest directrix. This value is constant for any conic section, and can define the conic section as well:

  - If $e = 1$, the conic is a parabola.
  - If $e < 1$, it is an ellipse.
  - If $e > 1$, it is a hyperbola.

The eccentricity of a circle is zero. The directrix of a conic section is the line that, together with the point known as the focus, serves to define a conic section. Hyperbolas and noncircular ellipses have two foci and two associated directrices. Parabolas have one focus and one directrix.
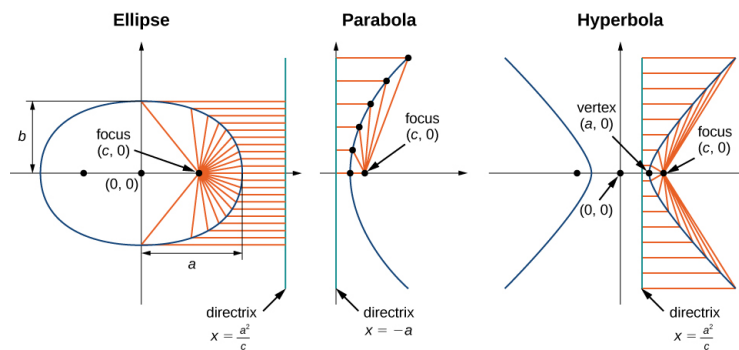
- **Eccentricity for parabola**

$$e = 1.$$

- **Eccentricity for ellipses**

$$e = \frac{c}{a}.$$

- **Eccentricity for hyperbolas**

$$e = \frac{c}{a}.$$

- A set of lines parallel to a given line passing through a given curve is known as a **cylindrical surface**, or cylinder. The parallel lines are called **rulings**.

- The **traces** of a surface are the cross-sections created when the surface intersects a plane parallel to one of the coordinate planes.

- We have learned about surfaces in three dimensions described by first-order equations; these are planes. Some other common types of surfaces can be described by second-order equations. We can view these surfaces as three-dimensional extensions of the conic sections we discussed earlier: the ellipse, the parabola, and the hyperbola. We call these graphs **quadric surfaces**.

- **Quadric surfaces** are the graphs of equations that can be expressed in the form

$$Ax^2 + By^2 + Cz^2 + Dxy + Exz + Fyz + Gx + Hy + Jz + K = 0..$$

  Note: When a quadric surface intersects a coordinate plane, the trace is a conic section.

- An **ellipsoid** is a surface described by an equation of the form

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1.$$

  Note: Set $x = 0$ to see the trace of the ellipsoid in the yz-plane. To see the traces in the xy- and xz-planes, set $z = 0$ and $y = 0$, respectively. Notice that, if $a = b$, the trace in the xy-plane is a circle. Similarly, if $a = c$, the trace in the xz-plane is a circle and, if $b = c$, then the trace in the yz-plane is a circle. A sphere, then, is an ellipsoid with $a = b = c$.
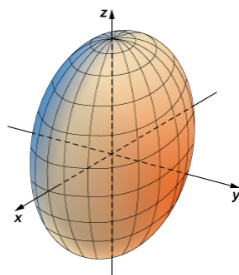
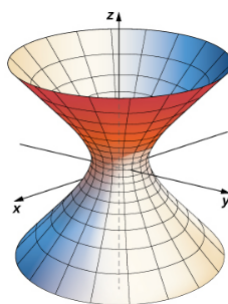- A **Sphere** is an ellipsoid with

$$a = b = c.$$

  Traces: All three traces are ellipses

- A quadric surface can have at most **two unique traces**, these traces make the name of the surface.

- **Hyperboloid of one sheet**

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} - \frac{z^2}{c} = 1.$$

  Two of the variables have positive coefficients and one has a negative coefficient. The axis of the surface corresponds to the variable with the negative coefficient
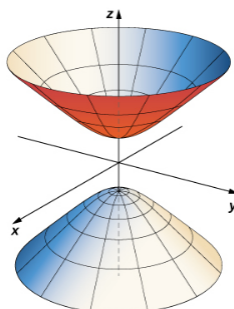

  Traces: One ellipse and two hypebolas

- **Hyperboloid of two sheets**

$$\frac{z^2}{c^2} - \frac{x^2}{a^2} - \frac{y^2}{b} = 1.$$

  Two of the variables have negative coefficients and one has a positive coefficient. The axis of the surface corresponds to the variable with the positive coefficient. The surface does not intersect the coordinate plane perpendicular to the axis
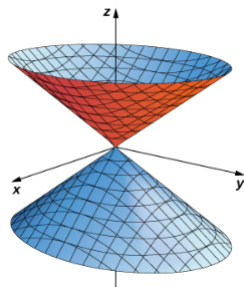
Traces: One ellipse (or the empty set (no trace)), and two hypebolas

- **Elliptic cone**

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} - \frac{z^2}{c^2} = 0.$$

The axis of the surface corresponds to the variable with a negative coefficient. The traces in the coordinate planes parallel to the axis are intersecting lines
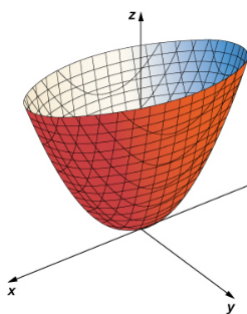

Traces: One ellipse and two hyperbolas.

In the xz-plane, we have a pair of lines that intersect at the orgin

In the yz-plane, we have a pair of lines that intersect at the orgin

- **Elliptic paraboloid**

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = z.$$

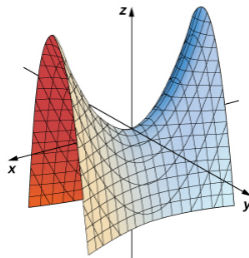The axis of the surface corresponds to the linear variable

Traces: One ellipse and two parabolas

- **Hyperbolic paraboloid**

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = z.$$

The axis of the surface corresponds to the linear variable

Traces: One hypebola and two parabolas

3.3   Chapter 3: Vector-Valued Functions

3.3.1   Definitions and Theorems

- A **vector-valued function** is a function of the form

$$\mathbf{r}(t) = f(t)\mathbf{i} + g(t)\mathbf{j} \quad \text{or} \quad \mathbf{r}(t) = f(t)\mathbf{i} + g(t)\mathbf{j} + h(t)\mathbf{k},$$

  where the **component functions** f, g, and h, are real-valued functions of the parameter t. Vector-valued functions are also written in the form

$$\mathbf{r}(t) = \langle f(t), g(t) \rangle \quad \text{or} \quad \mathbf{r}(t) = \langle f(t), g(t), h(t) \rangle.$$

  In both cases, the first form of the function defines a two-dimensional vector-valued function; the second form describes a three-dimensional vector-valued function.

  Note: The parameter t can lie between two real numbers: $a \leqslant t \leqslant b$ Another possibility is that the value of t might take on all real numbers. Last, the component functions themselves may have domain restrictions that enforce restrictions on the value of t. We often use t as a parameter because t can represent time.

- **Graphing vector-valued functions: Plane curve**: The graph of a vector-valued function of the form $\mathbf{r}(t) = f(t)\mathbf{i} + g(t)\mathbf{j}$ consists of the set of all $(t, \mathbf{r}(t))$, and the path it traces is called a **plane curve.**

- **Graphing vector-valued functions: Space curve**: The graph of a vector-valued function of the form $\mathbf{r}(t) = f(t)\mathbf{i} + g(t)\mathbf{j} + h(t)\mathbf{k}$ consists of the set of all $(t, \mathbf{r}(t))$, and the path it traces is called a **space curve**.

- **Vector Parameterization**: Any representation of a plane curve or space curve using a vector-valued function is called a **vector parameterization** of the curve.

- **Note on graphing vector-valued functions:** When graphing a vector-valued function, we typically graph the vectors in the domain of the function in standard position, because doing so guarantees the uniqueness of the graph.

- **How to graph vector-valued functions**: As with any graph, we start with a table of values. We then graph each of the vectors in the second column of the table in standard position and connect the terminal points of each vector to form a curve
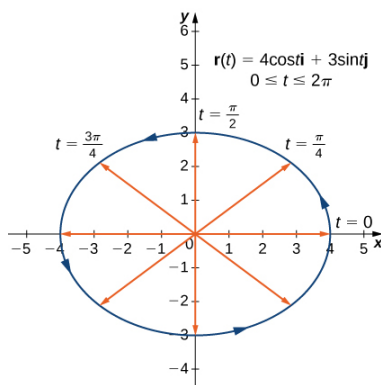
- **similarity between vector-valued functions and parameterized curves.**: Given a vector-valued function $\mathbf{r}(t) = f(t)\mathbf{i} + g(t)\mathbf{j}$, we can define $x = f(t)$ and $y = g(t)$. If a restriction exists on the values of t (for example, t is restricted to the interval $[a, b]$ for some constants $a < b$), then this restriction is enforced on the parameter. The graph of the parameterized function would then agree with the graph of the vector-valued function, except that the vector-valued graph would represent vectors rather than points. Since we can parameterize a curve defined by a function $y = f(x)$, it is also possible to represent an arbitrary plane curve by a vector-valued function.

- **Limits of a Vector-Valued Function (Rigorous)**: A vector-valued function $\mathbf{r}$ approaches the limit L as t approaches a, written

$$\lim_{t \to a} \mathbf{r}(t) = L,$$

provided

$$\lim_{t \to a} \|\mathbf{r}(t) - L\| = 0.$$

Note: This is a rigorous definition of the limit of a vector-valued function. In practice, we use the following theorem:

- **Limit of a Vector-Valued Function**: Let f, g, and h be functions of t. Then the limit of the vector-valued function $\mathbf{r}(t) = f(t)\mathbf{i} + g(t)\mathbf{j}$ as t approaches a is given by

$$\lim_{t \to a} \mathbf{r}(t) = \left[\lim_{t \to a} f(t)\right]\mathbf{i} + \left[\lim_{t \to a} g(t)\right]\mathbf{j},$$

provided the limits $\lim_{t \to a} f(t)$ and $\lim_{t \to a} g(t)$ exist. Similarly, the limit of the vector-valued function $\mathbf{r}(t) = f(t)\mathbf{i} + g(t)\mathbf{j} + h(t)\mathbf{k}$ as t approaches a is given by

$$\lim_{t \to a} \mathbf{r}(t) = \left[\lim_{t \to a} f(t)\right]\mathbf{i} + \left[\lim_{t \to a} g(t)\right]\mathbf{j} + \left[\lim_{t \to a} h(t)\right]\mathbf{k},$$

provided the limits $\lim_{t \to a} f(t)$, $\lim_{t \to a} g(t)$, and $\lim_{t \to a} h(t)$ exist.

- **Continuity of a vector-valued function**: Let f, g, and h be functions of t. Then, the vector-valued function $\mathbf{r}(t) = f(t)\mathbf{i} + g(t)\mathbf{j}$ is continuous at point $t = a$ if the following three conditions hold:

  1. $\mathbf{r}(a)$ exists.
  2. $\lim_{t \to a} \mathbf{r}(t)$ exists.
  3. $\lim_{t \to a} \mathbf{r}(t) = \mathbf{r}(a)$.

Similarly, the vector-valued function $\mathbf{r}(t) = f(t)\mathbf{i} + g(t)\mathbf{j} + h(t)\mathbf{k}$ is continuous at point $t = a$ if the following three conditions hold:

1. $\mathbf{r}(a)$ exists.
2. $\lim_{t \to a} \mathbf{r}(t)$ exists.
3. $\lim_{t \to a} \mathbf{r}(t) = \mathbf{r}(a)$.

- **Example problem**: Find the vector equation that represents the curve of intersection of the cylinder $x^2 + y^2 = 9$ and the surface $z = x + 3y$

To start, we can easily find $x(t)$ and $y(t)$.

Proposition.

$$x(t) = 3\cos t$$
$$y(t) = 3\sin t.$$

We can verify this simply

$$\frac{1}{3}x = \cos t$$
$$\frac{1}{3}y = \sin t.$$

If $\cos^2 t + \sin^2 t = 1$, Then

$$\frac{1}{9}x^2 + \frac{1}{9}y^2 = 1$$
$$x^2 + y^2 = 9.$$

To find the function for $z(t)$, we see that our surface is already solved for z, thus we simply replace x and y with what we have for $x(t)$ and $y(t)$

$$\implies z(t) = 3\cos t + 9\sin t.$$

- **The derivative of a vector-valued function** $r(t)$ The derivative of a vector-valued function $\mathbf{r}(t)$ is

$$\mathbf{r}'(t) = \lim_{\Delta t \to 0} \frac{\mathbf{r}(t + \Delta t) - \mathbf{r}(t)}{\Delta t}, \tag{25}$$

provided the limit exists. If $\mathbf{r}'(t)$ exists, then $\mathbf{r}$ is differentiable at t. If $\mathbf{r}'(t)$ exists for all t in an open interval (a, b), then $\mathbf{r}$ is differentiable over the interval (a, b). For the function to be differentiable over the closed interval $[a, b]$, the following two limits must exist as well:

$$\mathbf{r}'(a) = \lim_{\Delta t \to 0^+} \frac{\mathbf{r}(a + \Delta t) - \mathbf{r}(a)}{\Delta t} \tag{26}$$

and

$$\mathbf{r}'(b) = \lim_{\Delta t \to 0^-} \frac{\mathbf{r}(b + \Delta t) - \mathbf{r}(b)}{\Delta t}. \tag{27}$$

- **Differentiation of Vector-Valued Functions** Let f, g, and h be differentiable functions of t.

  − If $\mathbf{r}(t) = f(t)\mathbf{i} + g(t)\mathbf{j}$, then $\mathbf{r}'(t) = f'(t)\mathbf{i} + g'(t)\mathbf{j}$.
  − If $\mathbf{r}(t) = f(t)\mathbf{i} + g(t)\mathbf{j} + h(t)\mathbf{k}$, then $\mathbf{r}'(t) = f'(t)\mathbf{i} + g'(t)\mathbf{j} + h'(t)\mathbf{k}$.

- **Properties of the Derivative of Vector-Valued Functions**