

Quantum Math

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Algebra



Algebra Overview

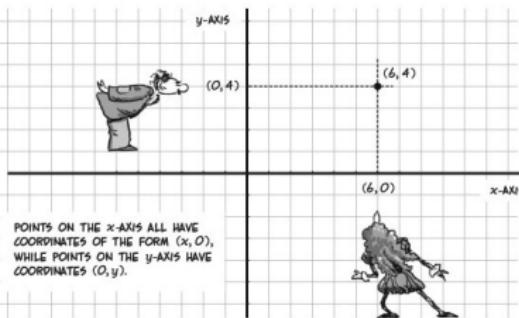
- Functions
- Transformations
- Polynomials
- Rational Functions
- Exponentials and Logarithms



Cartesian Coordinates

Cartesian coordinates is a system of describing the position of points in space using perpendicular axis lines that meet at a point called the origin. Any given point's position can be described based on its distance from the origin along each axis.

THE HORIZONTAL NUMBER LINE IS OFTEN CALLED THE x -AXIS AND THE VERTICAL NUMBER LINE THE y -AXIS. THE TWO NUMBERS OF A POINT'S ADDRESS ARE CALLED ITS x -COORDINATE AND ITS y -COORDINATE. TO FIND A POINT'S x -COORDINATE, FOLLOW A VERTICAL LINE FROM THE POINT TO THE x -AXIS; TO FIND ITS y -COORDINATE, GO HORIZONTALLY FROM THE POINT TO THE y -AXIS.



POINTS ON THE x -AXIS ALL HAVE COORDINATES OF THE FORM $(x, 0)$, WHILE POINTS ON THE y -AXIS HAVE COORDINATES $(0, y)$.

IF A CITY WERE LAID OUT LIKE THIS (AND MANY ARE—CHECK OUT A MAP OF NEW YORK CITY'S MANHATTAN), YOU MIGHT SAY THAT THE POINT (x, y) IS AT THE INTERSECTION OF x AVENUE AND y STREET. OF COURSE, OUR 'CITY' HAS FRACTIONAL AND IRRATIONAL STREETS, TOO...





Measuring Distance - Pythagorean Theorem

Pythagorean Theorem:

$$a^2 + b^2 = c^2$$

For example:

$$d^2 = 3^2 + 4^2$$

$$d^2 = 9 + 16 = 25$$

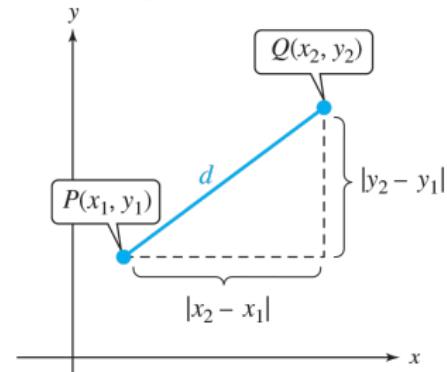
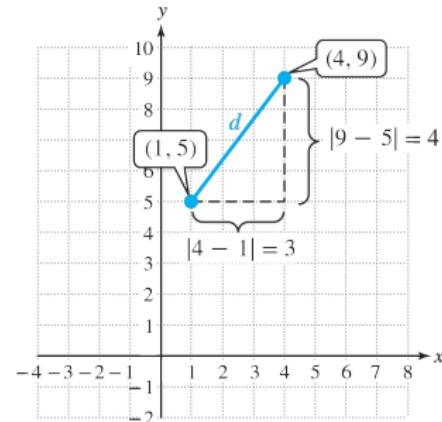
$$d = \sqrt{25} = 5$$

More generally for two points
 $P(x_1, y_1)$ and $Q(x_2, y_2)$

$$d^2 = (x_2 - x_1)^2 + (y_2 - y_1)^2$$

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

Noting that $|a| = (a)^2$:





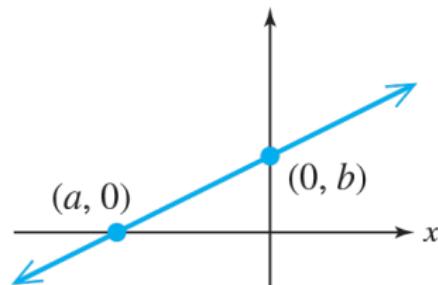
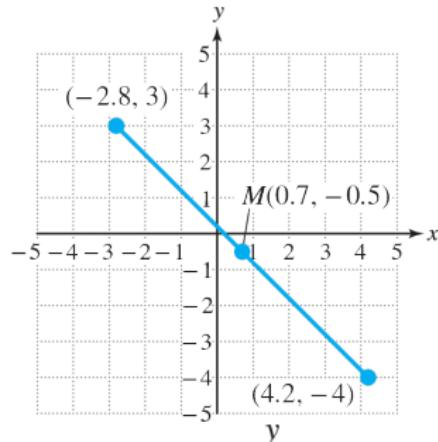
Midpoints and Intercepts

Midpoint:

$$M = \left(\frac{x_1+x_2}{2}, \frac{y_2+y_1}{2} \right)$$

Intercepts:

Two key features of a graph are where the graph intersects the x and y axes, the x-intercept and y-intercept, respectively.





The Circle

A circle is a set of all points that are equidistant from a fixed point called the center (h, k) . The distance from any point on the circle to the center is called the radius (r)

$$r = \sqrt{(x - h)^2 + (y - k)^2}$$

Equation of a circle:

Standard form: $(x - h)^2 + (y - k)^2 = r^2$

Expand binomials:

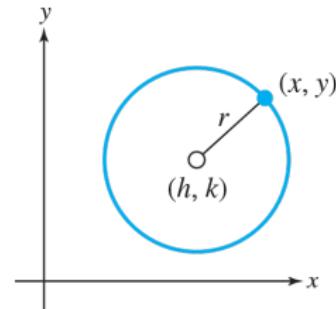
$$x^2 - hx + h^2 + y^2 - ky + k^2 - r^2 = 0$$

General form:

$$x^2 + y^2 - hx - ky + (h^2 + k^2 - r^2) = 0$$

or

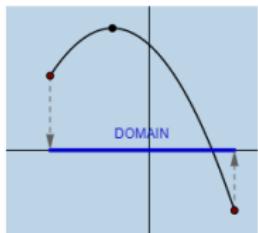
$$x^2 + y^2 + Ax + By + C = 0$$



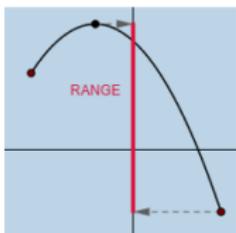


Domain and Range

Domain and Range



Domain is all the possible x values of a function.



Range is all the possible y values of a function.

A set of ordered pairs (x, y) is called a relation in x and y .

- The set of x -values in the ordered pairs is called the domain of the relations.
- The set of y -values in the ordered pairs is called the range of the relations.



Linear Equations with Two Variables

A linear equation in variables x and y can be written in the standard form:

$$Ax + By = C \tag{1}$$

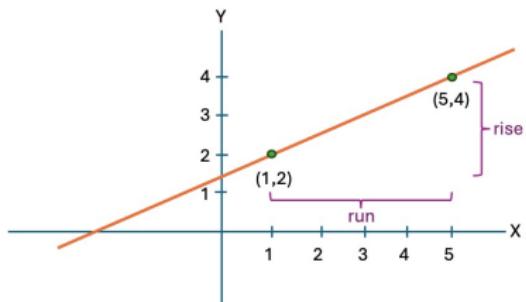
However, it is more common to see it in slope-intercept form:

$$y = mx + b \tag{2}$$

where, m is the slope and b is the y -intercept



Linear Conversion - Slope and Y-Intercept



$$y = mx + b$$

where m is slope and b y-intercept.

For example, given two points:

- $(x_1, y_1) = (1, 2)$
- $(x_2, y_2) = (5, 4)$

Find slope

- $m = \frac{\text{rise}}{\text{run}} = \frac{4-2}{5-1} = \frac{1}{2}$

Find y-intercept

- $y_1 = m * x_1 + b$
- $b = y_1 - (m * x_1)$
- $b = 2 - (\frac{1}{2} * 1) = 1\frac{1}{2}$

Use this to find the conversion from Celsius to Fahrenheit.

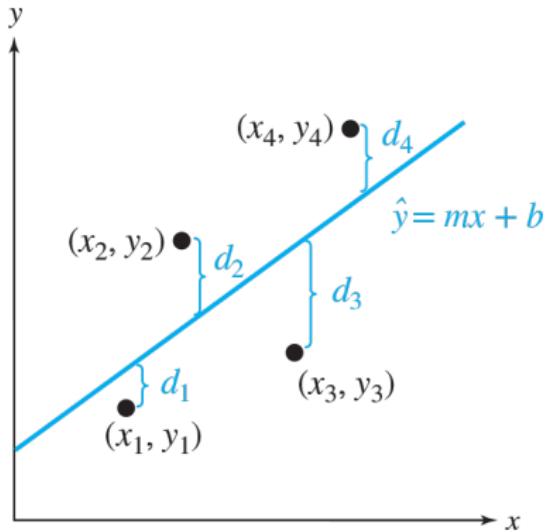


Parallel and Perpendicular Lines

| | | Relationship with Slopes (m) | | | | | | | | |
|--|----------------|---|--------|--------|---------------|----------------|---|----------------|----------------|---------------|
| Parallel Lines | | $m_1 = m_2$ | | | | | | | | |
| "Equal Slopes" | | Line 1 | Line 2 | | | | | | | |
| | $\frac{1}{3}$ | $\frac{1}{3}$ | | | | | | | | |
| 5 | 5 | | | | | | | | | |
| $-\frac{2}{7}$ | $-\frac{2}{7}$ | | | | | | | | | |
| Perpendicular Lines | | $m_1 = -\frac{1}{m_2}$ | | | | | | | | |
| "Opposite Reciprocal Slopes" | | <table border="1"> <thead> <tr> <th style="text-align: center;">Line 1</th><th style="text-align: center;">Line 2</th></tr> </thead> <tbody> <tr> <td style="text-align: center;">$\frac{1}{3}$</td><td style="text-align: center;">$-\frac{3}{1}$</td></tr> <tr> <td style="text-align: center;">5</td><td style="text-align: center;">$-\frac{1}{5}$</td></tr> <tr> <td style="text-align: center;">$-\frac{2}{7}$</td><td style="text-align: center;">$\frac{7}{2}$</td></tr> </tbody> </table> | Line 1 | Line 2 | $\frac{1}{3}$ | $-\frac{3}{1}$ | 5 | $-\frac{1}{5}$ | $-\frac{2}{7}$ | $\frac{7}{2}$ |
| Line 1 | Line 2 | | | | | | | | | |
| $\frac{1}{3}$ | $-\frac{3}{1}$ | | | | | | | | | |
| 5 | $-\frac{1}{5}$ | | | | | | | | | |
| $-\frac{2}{7}$ | $\frac{7}{2}$ | | | | | | | | | |
| | | | | | | | | | | |
| MATHguide.com | | | | | | | | | | |



Linear Regression



Consider a set of data:

$$(x_1, y_1), (x_2, y_2), (x_3, y_3), \dots, (x_n, y_n)$$

- The least-squares regression line $\hat{y} = mx + b$, is a unique line that minimizes the sum of the squared vertical deviations from the observed data points to the line.

Use this to find the conversion from Celsius to Fahrenheit.

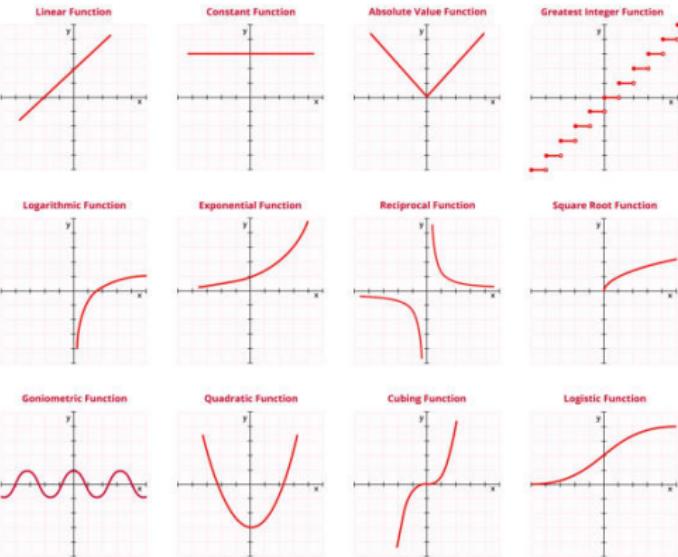


Recognizing Functions

An algebraic function provides a "y-value" for every "x-value"

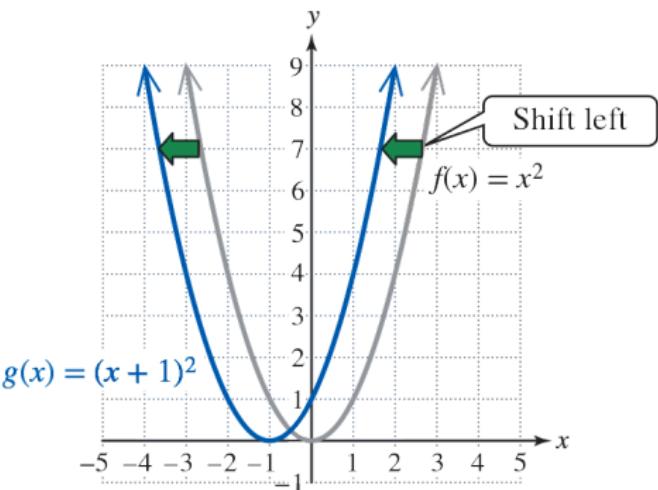
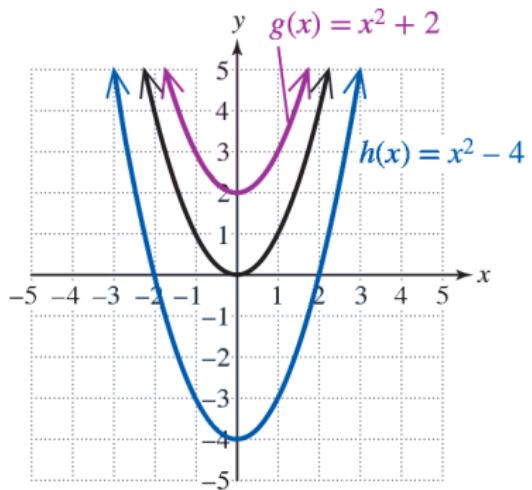
- Linear: $y = x + 2$
- Quadratic: $y = x^2$
- Periodic: $y = \sin(x)$

12 BASIC FUNCTIONS



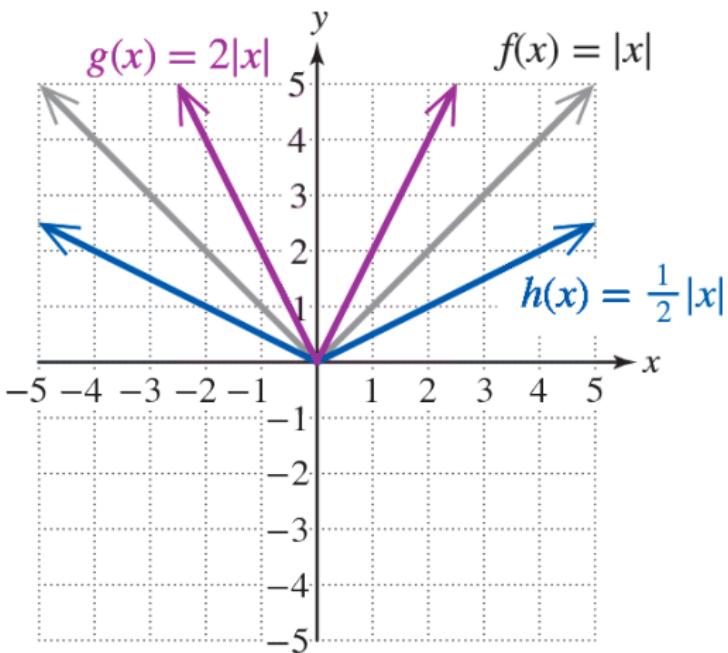


Vertical and Horizontal Shifts



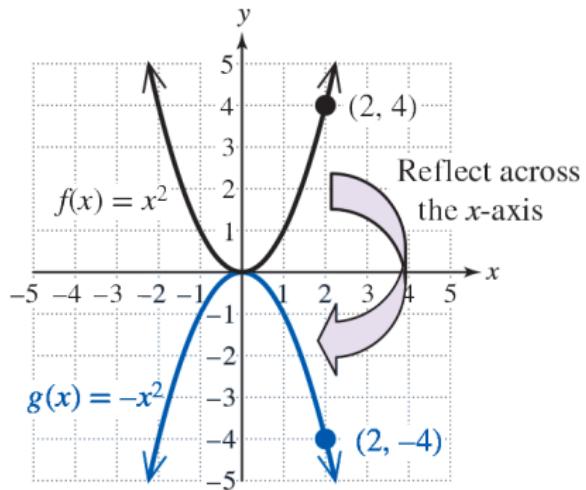
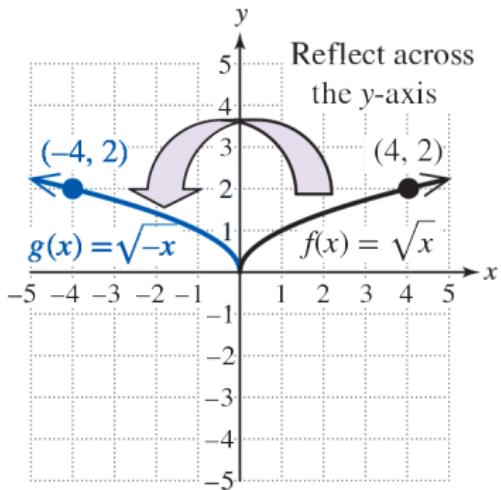


Shrink and Expand





X and Y Reflections



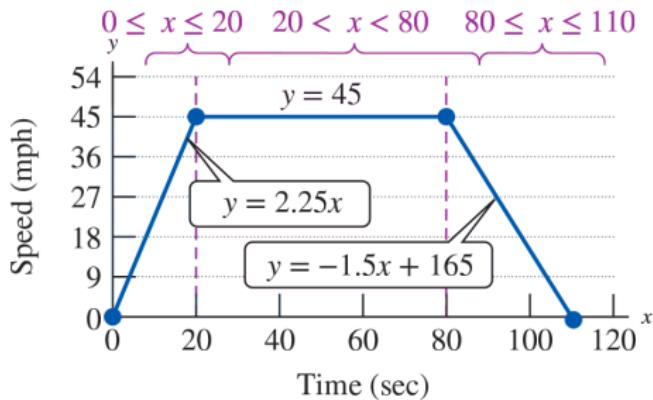


Summary - Transformations of Functions

| Transformation | Effect on the Graph of f | Changes to Points on f |
|---------------------------------------|---|--|
| Vertical translation (shift) | | |
| $y = f(x) + k$ $y = f(x) - k$ | Shift upward k units Shift downward k units | Replace (x, y) by $(x, y + k)$. Replace (x, y) by $(x, y - k)$. |
| Horizontal translation (shift) | | |
| $y = f(x - h)$ $y = f(x + h)$ | Shift to the right h units Shift to the left h units | Replace (x, y) by $(x + h, y)$. Replace (x, y) by $(x - h, y)$. |
| Vertical stretch/shrink | Vertical stretch (if $a > 1$) Vertical shrink (if $0 < a < 1$) Graph is stretched/shrunk vertically by a factor of a . | Replace (x, y) by (x, ay) . |
| Horizontal stretch/shrink | Horizontal shrink (if $a > 1$) Horizontal stretch (if $0 < a < 1$) Graph is shrunk/stretched horizontally by a factor of $\frac{1}{a}$. | Replace (x, y) by $(\frac{x}{a}, y)$. |
| Reflection | | |
| $y = -f(x)$ $y = f(-x)$ | Reflection across the x -axis Reflection across the y -axis | Replace (x, y) by $(x, -y)$. Replace (x, y) by $(-x, y)$. |



Piece-Wise Functions

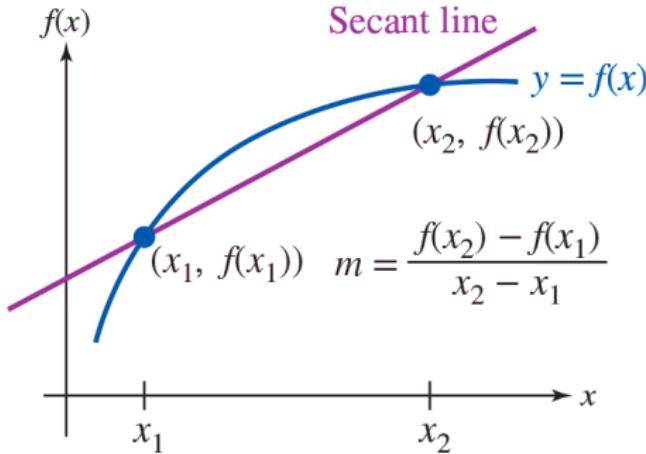


$$f(x) = \begin{cases} 2.25x & \text{for } 0 \leq x \leq 20 \\ 45 & \text{for } 20 < x < 80 \\ -1.5x + 165 & \text{for } 80 \leq x \leq 100 \end{cases}$$



Rate of Change

Given points (x_1, y_1) and (x_2, y_2) as points on the graph of a function $f()$, if $f()$ is defined on the interval $[x_1, x_2]$, then the average rate of change is the slope of the secant¹ line containing $(x_1, f(x_1))$ and $(x_2, f(x_2))$.

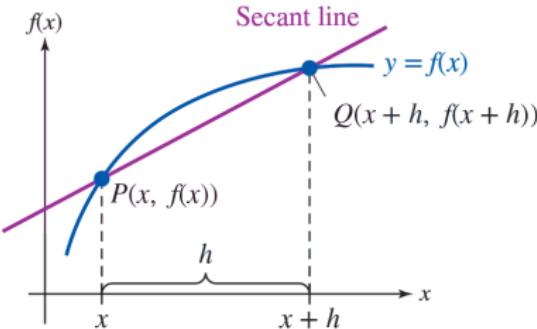


¹Secante comes from the latin secare meaning "to cut."



Difference Quotient

Suppose we choose a value x from the domain of $f()$ and a second value $x + h$, where $h \neq 0$, but very small.



The difference quotient².

$$m = \frac{f(x+h) - f(x)}{(x+h) - x} = \frac{f(x+h) - f(x)}{h} \quad (3)$$

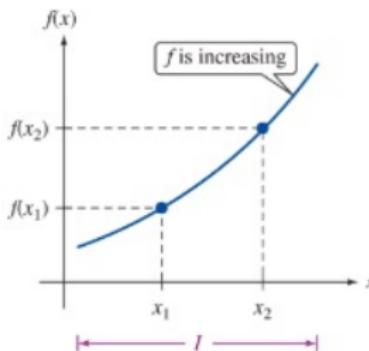
²The difference quotient is important to calculus, where the exact rate of change at a point is given by $\lim_{h \rightarrow 0}(m)$



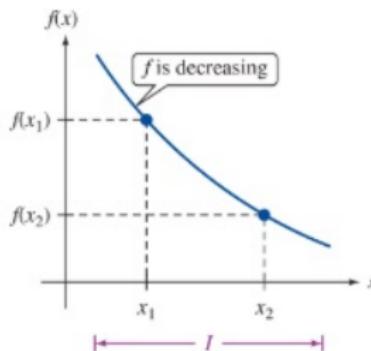
Increasing, Decreasing, Constant

Suppose that I is an interval contained within the domain of a function f .

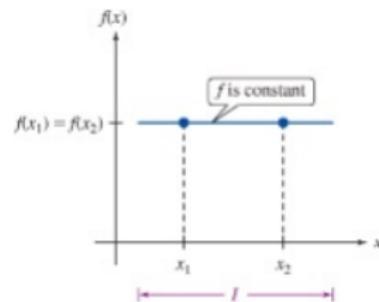
- f is increasing on I iff $f(x_1) < f(x_2)$ for all $x_1 < x_2$ on I .
- f is decreasing on I iff $f(x_1) > f(x_2)$ for all $x_1 < x_2$ on I .
- f is constant on I iff $f(x_1) = f(x_2)$ for all x_1 and x_2 on I .



For all $x_1 < x_2$ on I ,
 $f(x_1) < f(x_2)$



For all $x_1 < x_2$ on I ,
 $f(x_1) > f(x_2)$



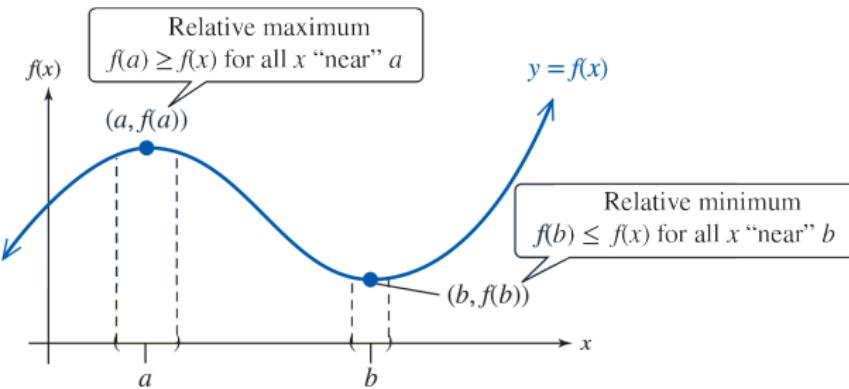
For all x_1 and x_2 on I ,
 $f(x_1) = f(x_2)$





Local Minima and Maxima

- $f(a)$ is a relative maximum of f if there exists an open interval³ containing a such that $f(a) \geq f(x)$ for all x in the interval.
- $f(b)$ is a relative minimum of f if there exists an open interval⁴ containing b such that $f(b) \leq f(x)$ for all x in the interval.



³An open interval is an interval in which the endpoints are not included.

⁴An open interval is an interval in which the endpoints are not included.

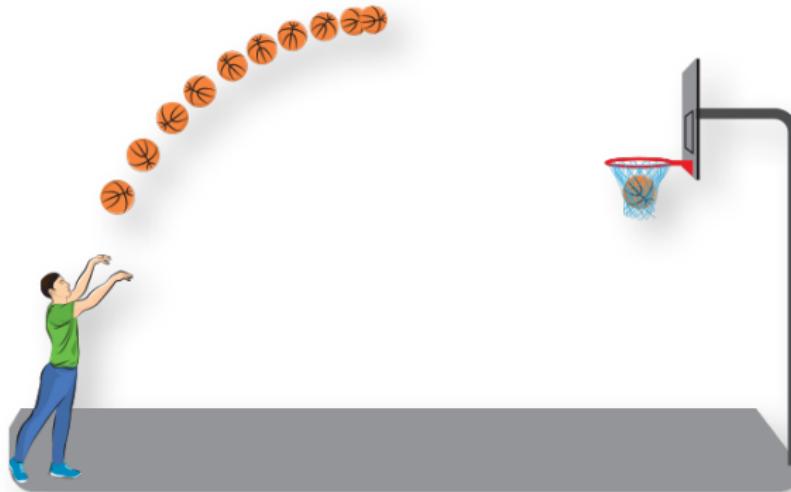


Operations on Functions



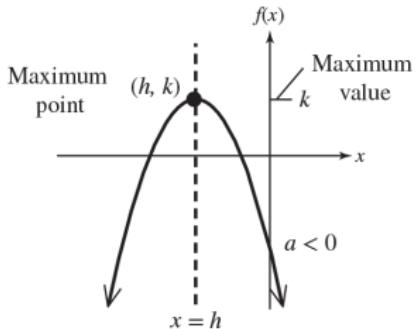
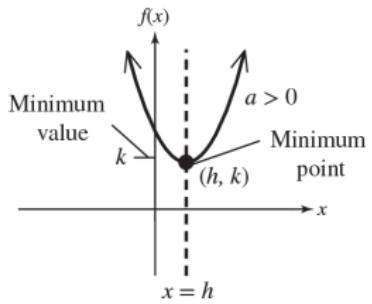
Quadratic Function

A quadratic function is often used as a model for the projectile motion. This is the motion followed by an object influenced by an initial force and by the force of gravity.





Quadratic Function - Vertex Form



Quadratic Function:

$$f(x) = ax^2 + bx + c \quad (a \neq 0)$$

By completing the square, it can be expressed in vertex form: $f(x) = a(x - h)^2 + k$

- The graph of $f(x)$ is a parabola with vertex (h, k)
- If $a > 0$ the parabola opens upward and minimum value is k .
- If $a < 0$ the parabola opens downward and maximum value is k .
- The axis of symmetry is $x = h$.



Polynomial Functions

Definition of a Polynomial Function

Let $a_n, a_{n-1}, a_{n-2}, \dots, a_0$ represent real numbers and $n, n - 1, n - 2, \dots, 0$ represent whole numbers. Then a function defined by

$$f(x) = a_nx^n + a_{n-1}x^{n-1} + a_{n-2}x^{n-2} + \dots + a_1x + a_0$$

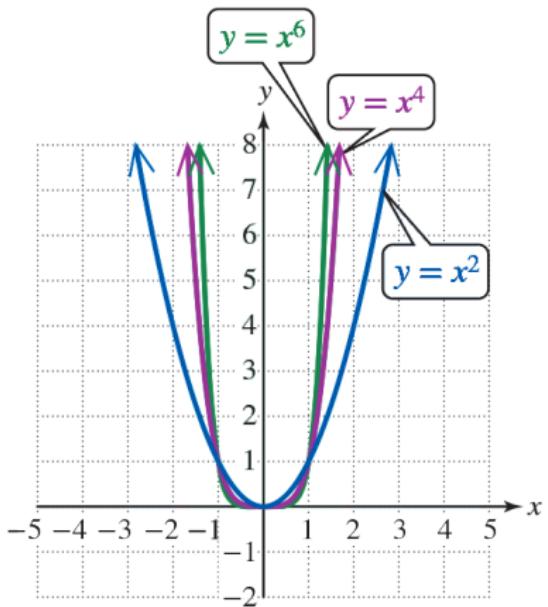
is called a **polynomial function**.

The term a_nx^n is called the **leading term**, the coefficient a_n is the **leading coefficient**, and the exponent n is the **degree** of the polynomial function.

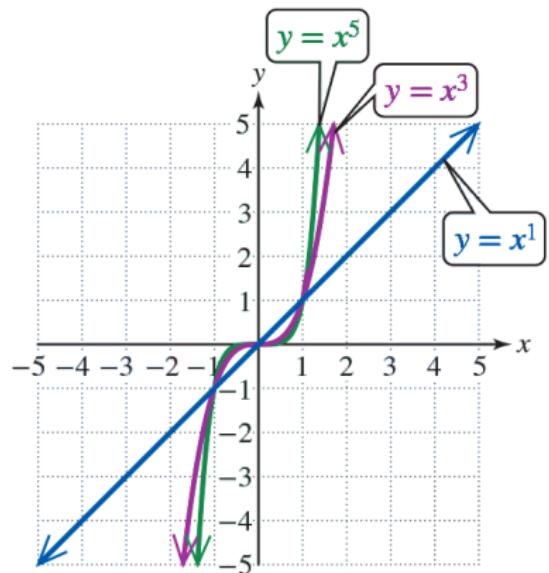


Even and Odd Exponents

Even:



Odd:





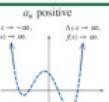
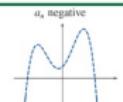
Polynomial End Behavior

The Leading Term Test

Consider a polynomial function given by

$$f(x) = a_n x^n + a_{n-1} x^{n-1} + a_{n-2} x^{n-2} + \cdots + a_1 x + a_0.$$

As $x \rightarrow \infty$ or as $x \rightarrow -\infty$, the graph of f will eventually have no more turns and will become forever increasing or forever decreasing. Thus, the graph of f far to the left and far to the right will follow the general behavior of $y = a_n x^n$.

| n is even | n is odd |
|---|--|
|  <p>a_n positive $\lim_{x \rightarrow \infty} f(x) = \infty$, $\lim_{x \rightarrow -\infty} f(x) = \infty$.</p> <p>End behavior: up left/up right</p> |  <p>a_n negative $\lim_{x \rightarrow \infty} f(x) = -\infty$, $\lim_{x \rightarrow -\infty} f(x) = \infty$.</p> <p>End behavior: down left/down right</p> |
|  |  |



Polynomial Finding Zeros



Rational Functions

Definition of a Rational Function

Let $p(x)$ and $q(x)$ be polynomials where $q(x) \neq 0$. A function f defined by

$f(x) = \frac{p(x)}{q(x)}$ is called a **rational function**.

Note: The domain of a rational function is all real numbers excluding the real zeros of $q(x)$.

| Function | Factored Form | Domain |
|--------------------------------------|---------------------------------------|--|
| $f(x) = \frac{1}{x}$ | $f(x) = \frac{1}{x}$ | $\{x x \neq 0\}$ $(-\infty, 0) \cup (0, \infty)$ |
| $g(x) = \frac{5x^2}{2x^2 + 5x - 12}$ | $g(x) = \frac{5x^2}{(2x - 3)(x + 4)}$ | $\{x x \neq \frac{3}{2}, x \neq -4\}$ $(-\infty, -4) \cup (-4, \frac{3}{2}) \cup (\frac{3}{2}, \infty)$ |
| $k(x) = \frac{x + 3}{x^2 + 4}$ | $k(x) = \frac{x + 3}{x^2 + 4}$ | \mathbb{R} $(-\infty, \infty)$ |



Exponential Functions

- Linear growth - a constant rate of change, that is, a constant number by which the output increased for each unit increase in input.
- Exponential growth - increase based on a constant multiplicative rate of change over equal increments of time, that is, a percent increase of the original amount over time.

| x | $f(x) = 2^x$ | $g(x) = 2x$ |
|-----|--------------|-------------|
| 0 | 1 | 0 |
| 1 | 2 | 2 |
| 2 | 4 | 4 |
| 3 | 8 | 6 |
| 4 | 16 | 8 |
| 5 | 32 | 10 |
| 6 | 64 | 12 |



Origami to the Moon

Fold a piece of paper 42 times and you will reach the moon

Thickness in kilometres

450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0

This shows:

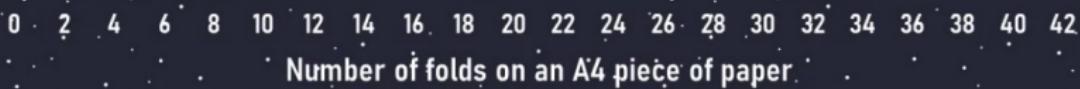
1. How exponential growth works
2. The power of compounding in action
3. Why stopping the coronavirus early is important



439,805 km



384,400 km



Note: simulation based on an 80 gm piece of paper has a 0.1mm thickness.

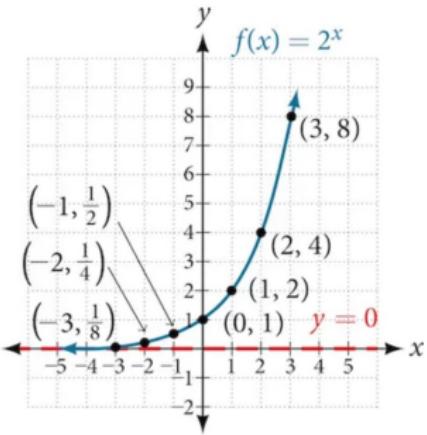


What about Negative Exponents

The general form of an exponential function is $f(x) = ab^x$, where a is any non-zero number and b is a positive number not equal to 1.

- If $b > 1$ the function grows at a rate proportional to its size.
- If $0 < b < 1$ the function decays at a rate proportional to its size.

For example, $f(x) = 2^x$:



| x | -3 | -2 | -1 | 0 | 1 | 2 | 3 |
|--------------|------------------------|------------------------|------------------------|-----------|-----------|-----------|-----------|
| $f(x) = 2^x$ | $2^{-3} = \frac{1}{8}$ | $2^{-2} = \frac{1}{4}$ | $2^{-1} = \frac{1}{2}$ | $2^0 = 1$ | $2^1 = 2$ | $2^2 = 4$ | $2^3 = 8$ |



Scientific (SI) Prefixes

The Metric System Prefixes

| Prefix | Label | Decimal Value | Scientific | Colloquial |
|--------|-------|-----------------------------------|------------|---------------|
| yocto | y | 0.000 000 000 000 000 000 000 001 | 10^{-24} | septillionth |
| zepto | z | 0.000 000 000 000 000 000 000 001 | 10^{-21} | sextillionth |
| atto | a | 0.000 000 000 000 000 000 001 | 10^{-18} | quintillionth |
| femto | f | 0.000 000 000 000 001 | 10^{-15} | quadrillionth |
| pico | p | 0.000 000 001 | 10^{-12} | trillionth |
| nano | n | 0.000 000 001 | 10^{-9} | billionth |
| micro | μ | 0.000 001 | 10^{-6} | millionth |
| milli | m | 0.001 | 10^{-3} | thousandth |
| centi | c | 0.01 | 10^{-2} | hundredth |
| deci | d | 0.1 | 10^{-1} | tenth |
| — | — | 1 | 10^0 | one |
| deka | da | 10 | 10^1 | ten |
| hecto | h | 100 | 10^2 | hundred |
| kilo | k | 1 000 | 10^3 | thousand |
| mega | M | 1 000 000 | 10^6 | million |
| giga | G | 1 000 000 000 | 10^9 | billion |
| tera | T | 1 000 000 000 000 | 10^{12} | trillion |
| peta | P | 1 000 000 000 000 000 | 10^{15} | quadrillion |
| exa | E | 1 000 000 000 000 000 000 | 10^{18} | quintillion |
| zetta | Z | 1 000 000 000 000 000 000 000 | 10^{21} | sextillion |
| yotta | Y | 1 000 000 000 000 000 000 000 000 | 10^{24} | septillion |



e - an interesting aside

The letter e represents the irrational number:

$$e = \left(1 + \frac{1}{n}\right)^n \quad (4)$$

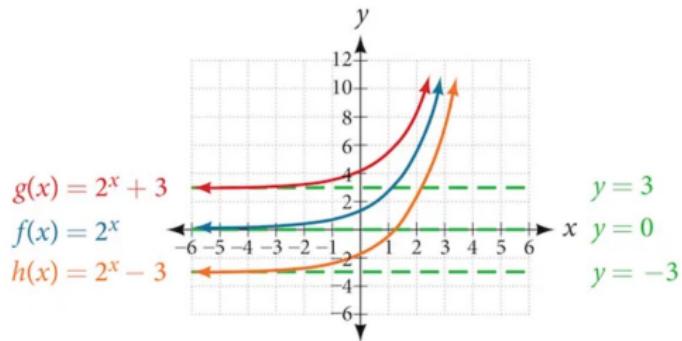
as n increases without bound.

The number e is used as a base for many real-world exponential models. To work with base e , we use the approximation, $e \approx 2.718282$. The constant was named by the Swiss mathematician Leonhard Euler (1707–1783) who first investigated and discovered many of its properties.

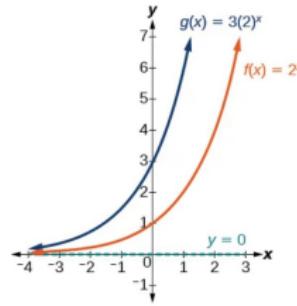


Graphing Exponentials

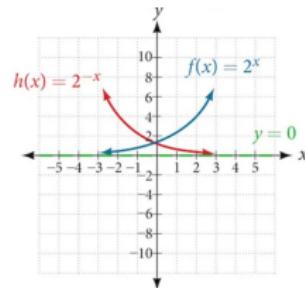
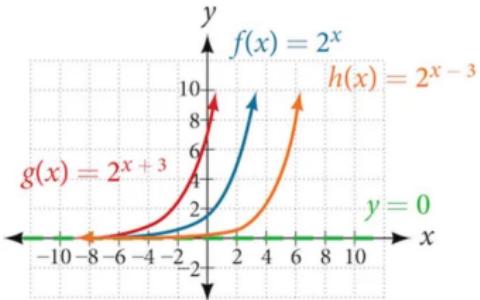
Shifts:



Stretch:



Flip:





Logarithmic Functions

Definition of a Logarithmic Function

If x and b are positive real numbers such that $b \neq 1$, then $y = \log_b x$ is called the **logarithmic function base b** , where

$$y = \log_b x \text{ is equivalent to } b^y = x$$

Notes:

- Given $y = \log_b x$, the value y is the exponent to which b must be raised to obtain x .
- The value of y is called the **logarithm**, b is called the **base**, and x is called the **argument**.
- The equations $y = \log_b x$ and $b^y = x$ both define the same relationship between x and y . The expression $y = \log_b x$ is called the **logarithmic form**, and $b^y = x$ is called the **exponential form**.



Natural Log

Definition of Common and Natural Logarithmic Functions

- The logarithmic function base 10 is called the **common logarithmic function**. The common logarithmic function is denoted by $y = \log x$. Notice that the base 10 is not explicitly written; that is, $y = \log_{10}x$ is written simply as $y = \log x$.
- The logarithmic function base e is called the **natural logarithmic function**. The natural logarithmic function is denoted by $y = \ln x$; that is, $y = \log_e x$ is written as $y = \ln x$.



Logarithmic Functions

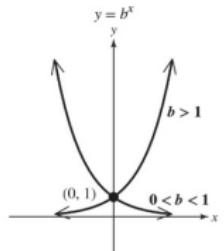
| Logarithmic form: $y = \log_b x$ | | Exponential form: $b^y = x$ |
|----------------------------------|--------|-----------------------------|
| $\log_2 16 = 4$ | \iff | $2^4 = 16$ |
| $\log_{10} \frac{1}{100} = -2$ | \iff | $10^{-2} = \frac{1}{100}$ |
| $\log_7 1 = 0$ | \iff | $7^0 = 1$ |



Graphing Exponential and Logarithmic Functions

Graphs of Exponential and Logarithmic Functions

Exponential Functions



Domain: $(-\infty, \infty)$

Range: $(0, \infty)$

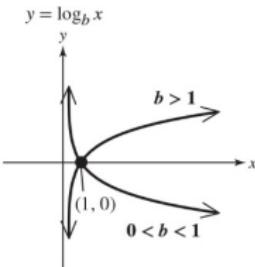
Horizontal asymptote: $y = 0$

Passes through $(0, 1)$

If $b > 1$, the function is increasing.

If $0 < b < 1$, the function is decreasing.

Logarithmic Functions



Domain: $(0, \infty)$

Range: $(-\infty, \infty)$

Vertical asymptote: $x = 0$

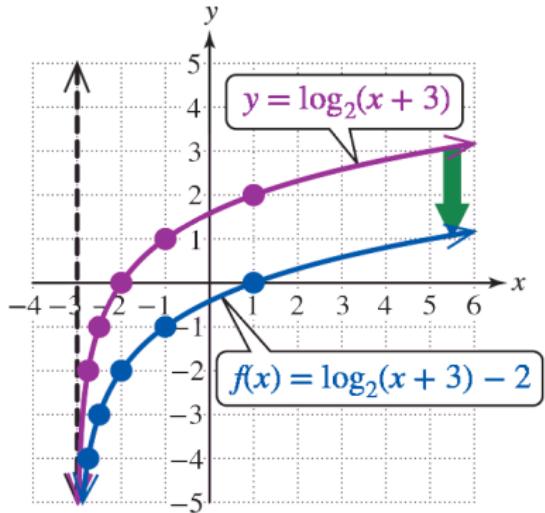
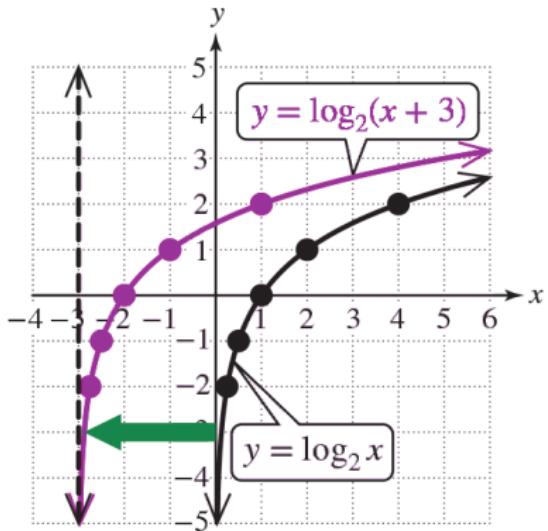
Passes through $(1, 0)$

If $b > 1$, the function is increasing.

If $0 < b < 1$, the function is decreasing.



Logarithmic Transforms





Logarithm Rules

- Product Property

$$\log_b(xy) = \log_b(x) + \log_b(y) \quad (5)$$

- Quotient Property

$$\log_b\left(\frac{x}{y}\right) = \log_b(x) - \log_b(y) \quad (6)$$

- Power Property

$$\log_b x^p = p \cdot \log_b x \quad (7)$$



Properties of Logarithms

Properties of Logarithms

Let b , x , and y be positive real numbers where $b \neq 1$, and let p be a real number. Then the following properties of logarithms are true.

1. $\log_b 1 = 0$

2. $\log_b b = 1$

3. $\log_b b^p = p$

4. $b^{\log_b x} = x$

5. $\log_b (xy) = \log_b x + \log_b y$ **Product property**

6. $\log_b \left(\frac{x}{y}\right) = \log_b x - \log_b y$ **Quotient property**

7. $\log_b x^p = p \log_b x$ **Power property**

Trigonometry

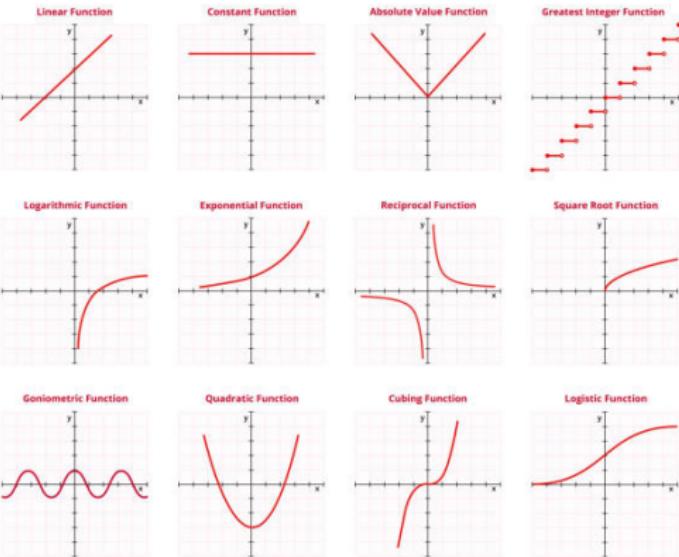


Algebraic Functions

An algebraic function provides a "y-value" for every "x-value"

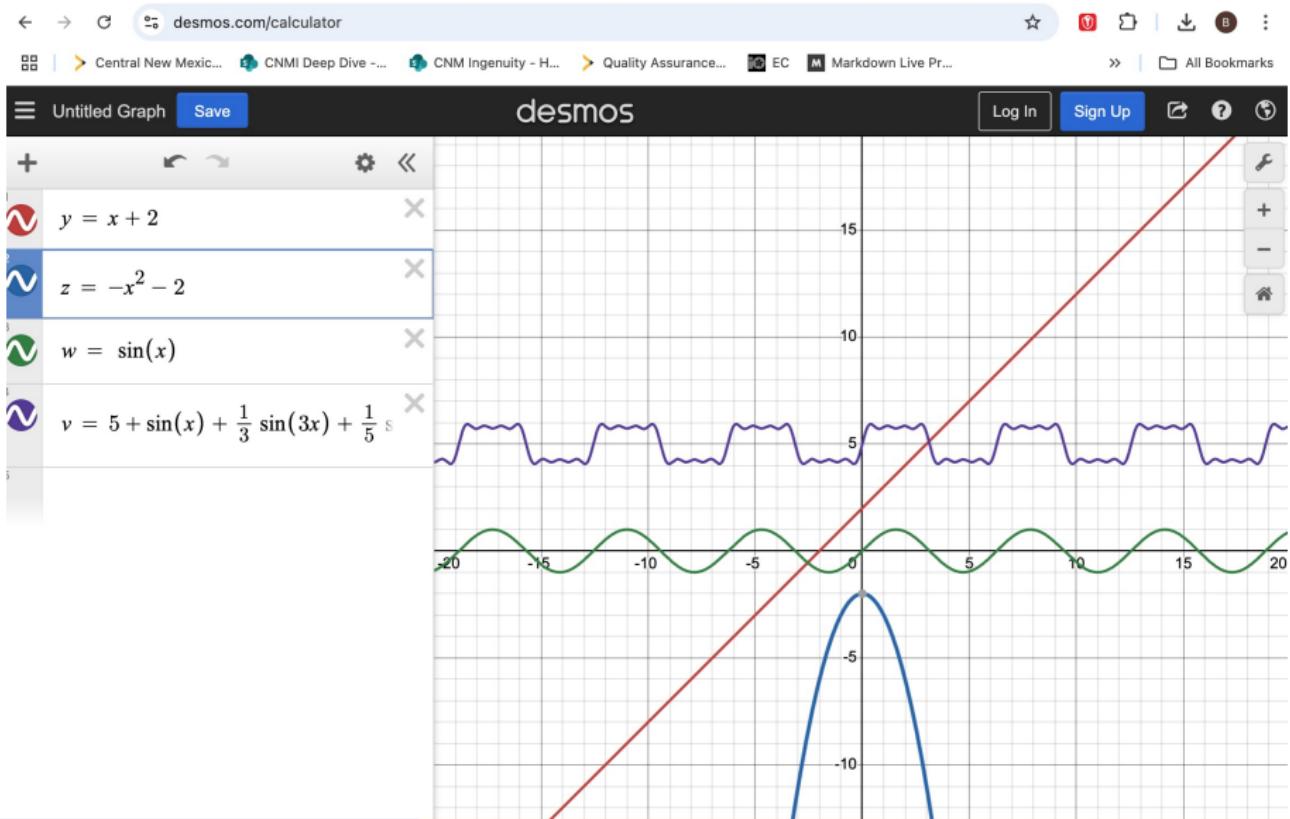
- Linear: $y = x + 2$
- Quadratic: $y = x^2$
- Periodic: $y = \sin(x)$

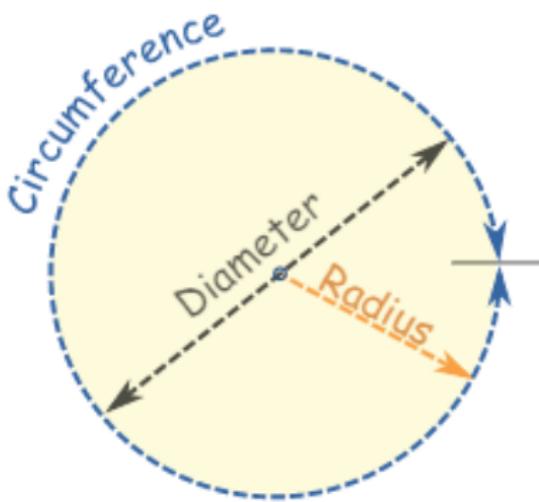
12 BASIC FUNCTIONS





More Desmos Fun



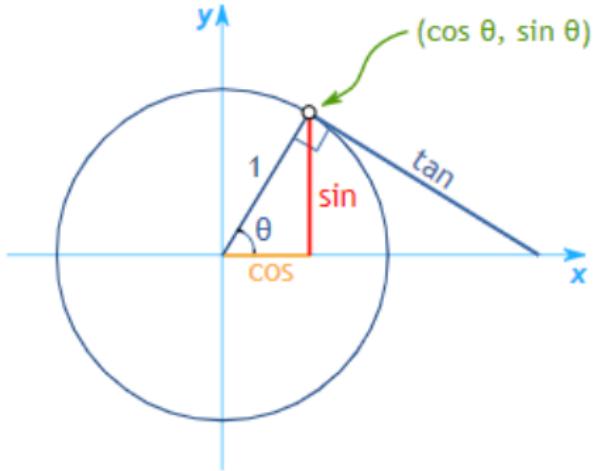
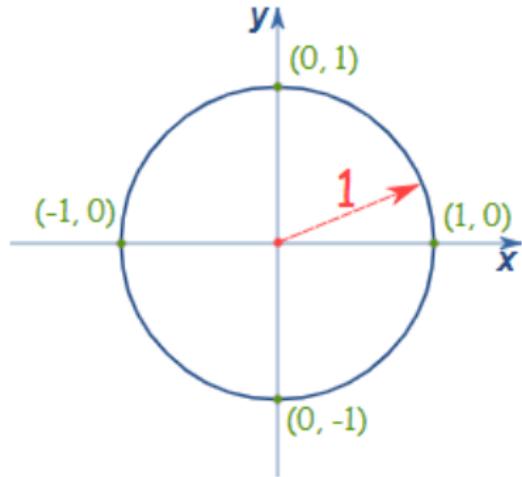
Pi (π)

$$\frac{\text{Circumference}}{\text{Diameter}} = \pi = 3.14159\dots$$



Unit Circle and Trigonometric Functions

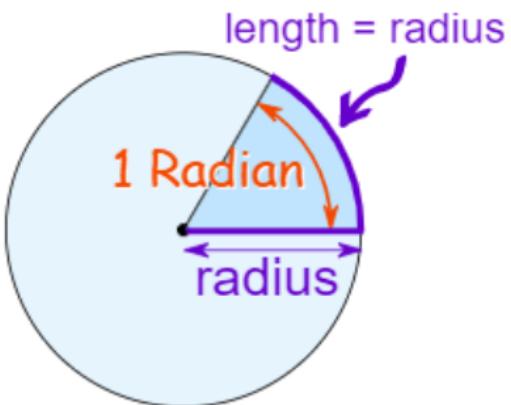
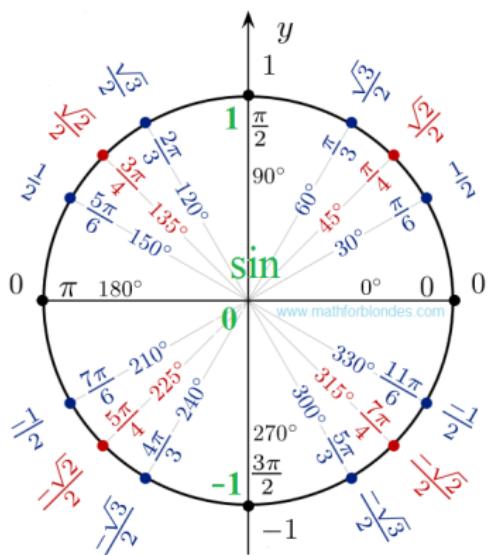
The Unit Circle is a circle with a radius of 1.



The Unit Circle can be used to map out the trigonometric values of sine, cosine, and tangent.



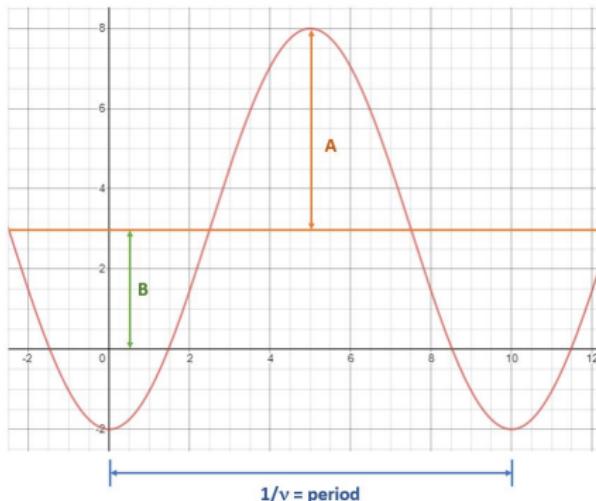
Unit Circle and the Value of $\sin(\theta)$



- $\sin(\theta)$ is the y-value of the point on the Unit Circle at angle θ .
- In our trig functions, θ is measured in radians (rad), not degrees.
- 360 degrees = 2π radians.



Sine Waves

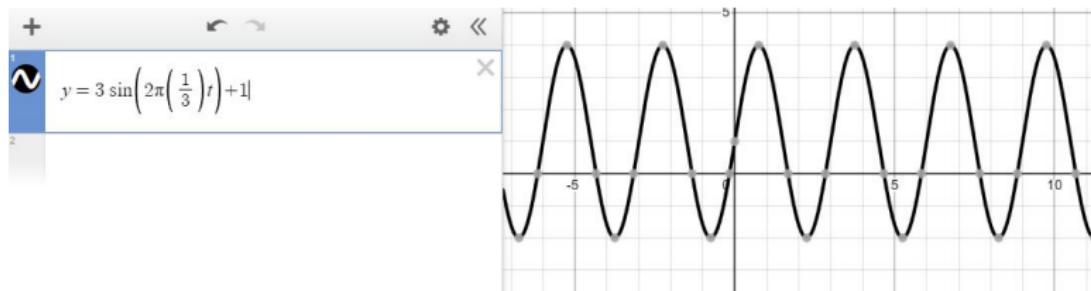
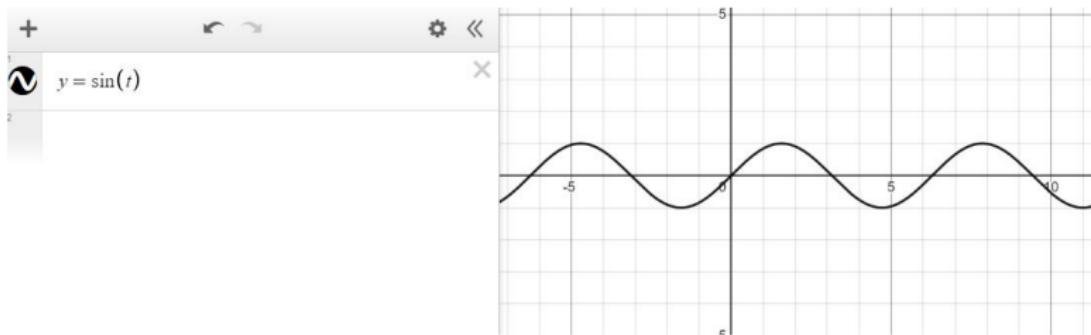


$$y = A * \sin(2 * \pi * \nu * t) + B$$

where A = amplitude, B = offset, ν = frequency = $\frac{1}{\text{period}}$,
and t = time in seconds.



Using Desmos (desmos.com/calculator)

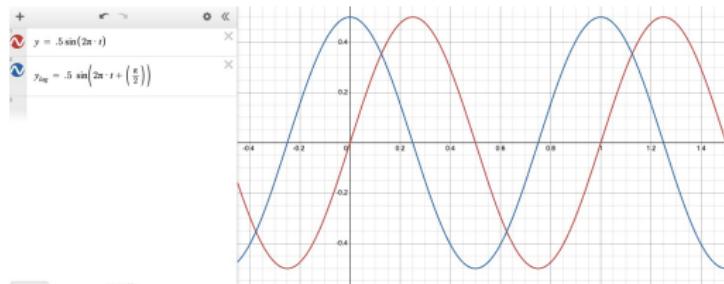




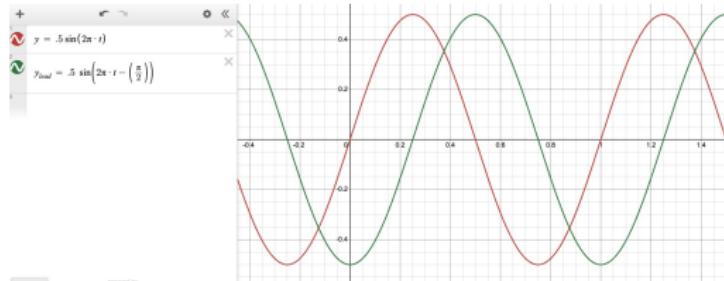
Phase Shift

The sine wave can be shifted relative to each other by adding in a phase shift (ϕ), which will shift the wave to the left or right.

Blue lags Red:



Green leads Red:





SOH CAH TOA

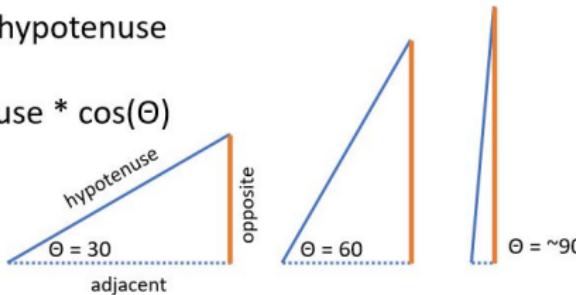
- $\sin = \text{opposite over hypotenuse}$
- $\cos = \text{adjacent over hypotenuse}$
- $\tan = \text{opposite over adjacent}$

$$\cos(\theta) = \text{adjacent} / \text{hypotenuse}$$

or

$$\text{Adjacent} = \text{hypotenuse} * \cos(\theta)$$

$$\theta = 0$$



$$\sin(\theta) = \text{opposite} / \text{hypotenuse}$$

or

$$\text{opposite} = \text{hypotenuse} * \sin(\theta)$$

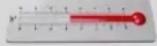
Vectors



Scalars and Vectors

Scalars are quantities that are fully described by a magnitude (or numerical value) alone.

Vectors are quantities that are fully described by both a magnitude and a direction.

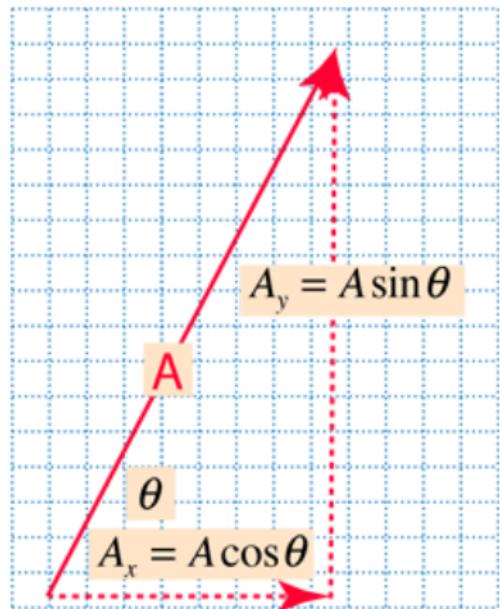
| Scalar | Vector |
|---|--|
|  Volume |  Time |
|  Temperature |  Speed |
| | |
|  Weight |  Thrust |
| | |
|  Magnetic field |  Velocity |



Vector Components

Finding the components of a vector involves forming a right triangle and using trigonometry's SOH-CAH-TOA

- $A_x = A\cos(\theta)$
- $A_y = A\sin(\theta)$

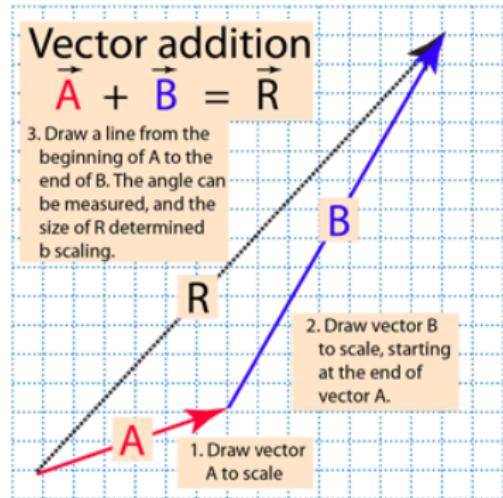




Graphical Vector Addition

Adding two vectors A and B graphically can be visualized like two successive walks, with the vector sum being the vector distance from the beginning to the end point.

Representing the vectors by arrows drawn to scale, the beginning of vector B is placed at the end of vector A. The vector sum R can be drawn as the vector from the beginning to the end point.

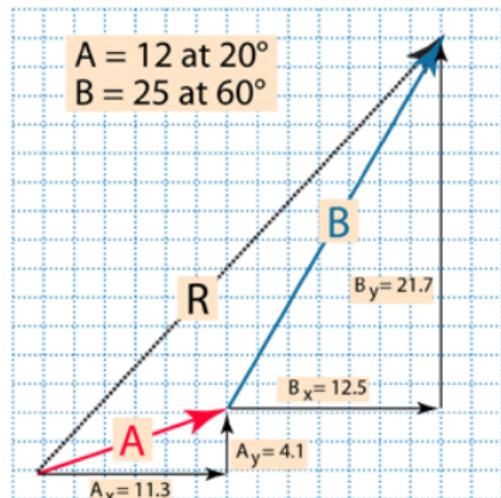




Vector Components

Finding the components of a vector involves forming a right triangle and using trigonometry's SOH-CAH-TOA

- Add the X components
 - $A_x = 12\cos(20^\circ) = 11.3$
 - $B_x = 25\cos(60^\circ) = 12.5$
 - $R_x = A_x + B_x = 23.8$
- Add the Y components
 - $A_y = 12\sin(20^\circ) = 4.1$
 - $B_y = 25\sin(60^\circ) = 21.7$
 - $R_y = A_y + B_y = 25.8$

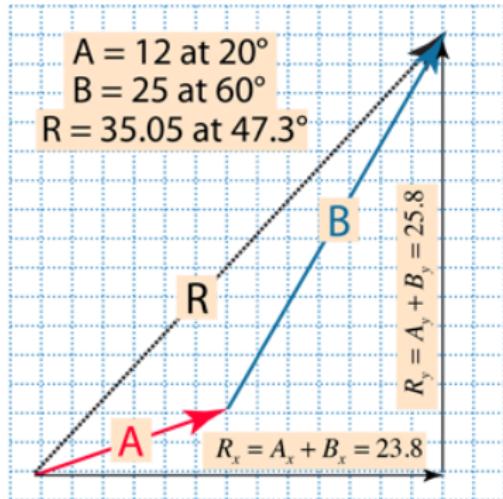




Polar Form

After finding the components, the result can be placed in Polar Form:

- $R_x = 23.8$
- $R_y = 25.8$
- $R = \sqrt{R_x^2 + R_y^2} = 35.05$
- $\theta_R = \tan^{-1}\left(\frac{R_y}{R_x}\right) = 47.3^\circ$



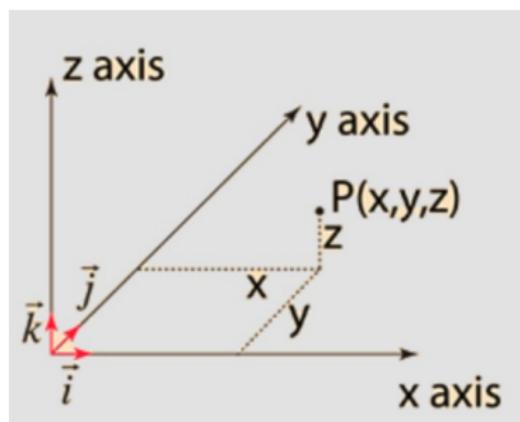


Unit Vectors in 3 Dimensions

Vectors of unit length (i.e., length equals 1) can be used to specify the direction of vector quantities in various coordinate systems.

In Cartesian coordinates, it is typical to use \vec{i} , \vec{j} , and \vec{k} to represent the unit vectors in the x , y , and z directions, respectively:

$$\vec{r} = x\vec{i} + y\vec{j} + z\vec{k} \quad (8)$$



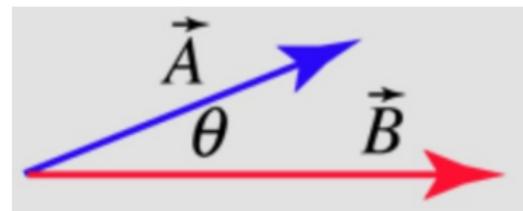


Dot (Scalar) Product

The dot (or inner or scalar) product of two vectors can be constructed by taking the component of the first vector in the direction of the second vector and by multiplying it by the second vector's magnitude.

$$\vec{A} \cdot \vec{B} = AB\cos(\theta) \quad (9)$$

or



$$\vec{A} \cdot \vec{B} = A_x B_x + A_y B_y + A_z B_z \quad (10)$$



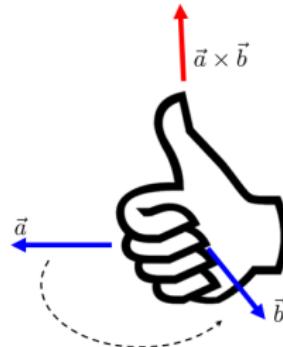
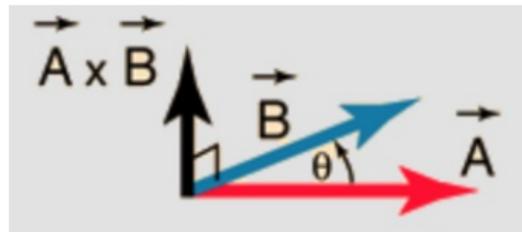
Cross (Vector) Product

The magnitude of the cross (or outer or vector) product of vectors can be constructed by taking the product of the magnitude of the vectors times the sine of the angle between them.

$$\vec{A} \times \vec{B}_{magnitude} = AB\sin(\theta) \quad (11)$$

and the direction is given by the right hand rule.

In terms of unit vectors:



$$\vec{A} \times \vec{B} = \vec{i}(A_y B_z - A_z B_y) + \vec{j}(A_z B_x - A_x B_z) + \vec{k}(A_x B_y - A_y B_x) \quad (12)$$



Bonus - Cross Product - Determinant Form

The cross product can be compactly stated in the form of a determinant:

$$\vec{A} \times \vec{B} = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ A_x & A_y & A_z \\ B_x & B_y & B_z \end{vmatrix}$$

Which can be expanded to

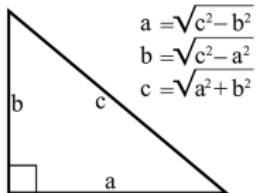
$$\vec{A} \times \vec{B} = \vec{i}(A_y B_z - A_z B_y) + \vec{j}(A_z B_x - A_x B_z) + \vec{k}(A_x B_y - A_y B_x)$$



Pythagorean Theorem in 3 Dimensions

The Pythagorean Theorem

$$c^2 = a^2 + b^2$$



$$a = \sqrt{c^2 - b^2}$$

$$b = \sqrt{c^2 - a^2}$$

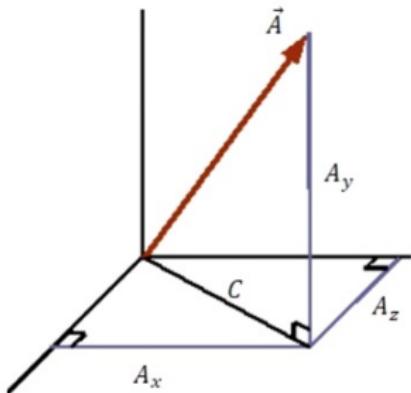
$$c = \sqrt{a^2 + b^2}$$

To add orthogonal (at right angles to each other) vectors in 3 Dimensions:

- $C = \sqrt{A_x^2 + A_y^2}$

- $A_{total} = \sqrt{C^2 + A_z^2}$

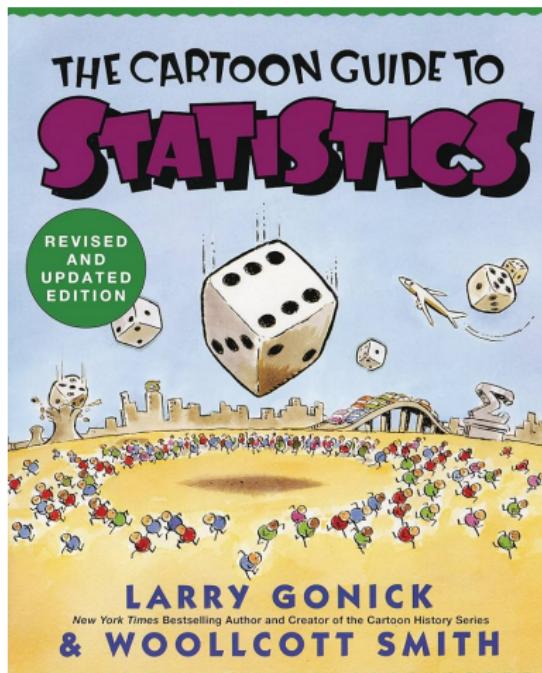
- $A_{total} = \sqrt{A_x^2 + A_y^2 + A_z^2}$



Probability and Statistics



Probability and Statistics



- Data Analysis: The gathering, display, and summary of data
- Probability: The laws of chance (inside and outside of a casino)
- Statistical Inference: the science of drawing statistical conclusions from specific data using the laws of probability



A Tale as Old as Time



Gambling is as old as mankind, so it seems that probability should be almost as old. But, the realization that one could predict an outcome to a certain degree of accuracy was unconceivable until the 16th century. In order to make a profit, underwriters were in need of dependable guidelines by which a profit could be expected, while the gambler was interested in predicting the possibility of gain.



Rich Guys Gambling



Known as the “Father of Probability”, Gerolamo Cardano was an Italian mathematician, physician, and gambler who first talked about probability. Cardano’s fascination with games of chance led him to write the first book dedicated to probability, “Liber de Ludo Aleae” (Book on Games of Chance), published in 1564. Cardano introduced concepts like odds and probabilities in this work, providing a framework for analyzing the likelihood of different outcomes in dice rolls and other games.



Probability

The probability of an event expresses the likelihood of the event outcome

$$P(\text{event}) = \frac{\# \text{ of favorable outcomes}}{\# \text{ of all possibly outcomes}}$$

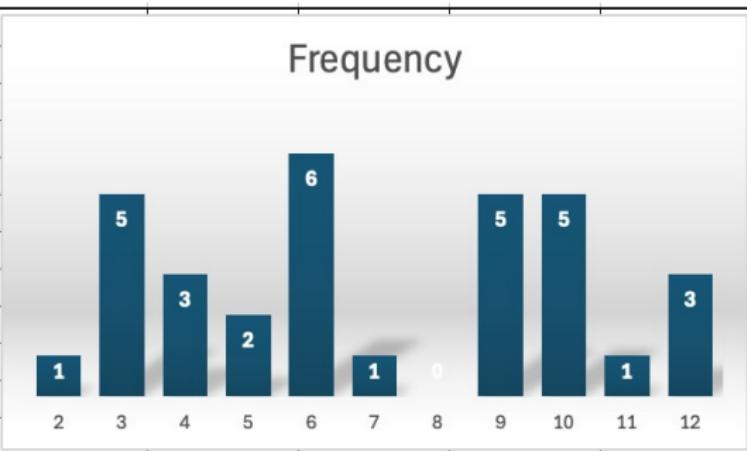




Frequency Tables and Histograms

Roll two dice and add them together, repeat.

| Dice Roll | Frequency |
|-----------|-----------|
| 2 | 1 |
| 3 | 5 |
| 4 | 3 |
| 5 | 2 |
| 6 | 6 |
| 7 | 1 |
| 8 | 0 |
| 9 | 5 |
| 10 | 5 |
| 11 | 1 |
| 12 | 3 |





Assignment: Tenzi



Role two dice 12 times, after each role:

- Record the sum
- Record the running average (total up to this point divided by number of roles)

After the twelfth role:

- Create a histogram of the sums
- Create a line chart of the running averages



Summary Statistics

- Mean (or average): add the totals and divide by number of samples

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \dots + x_n}{n}$$

or

$$\bar{x} = \frac{\sum_{i=1}^n (x_i)}{n}$$

- Median: middle sample in the ordered distribution
 - Odd: median is the value of middle sample
 - Even: median is the average of the two middle samples
- Mode: the value that appears most often

| Dice Roll | Frequency | Total |
|------------|-----------|------------|
| 2 | 1 | 2 |
| 3 | 5 | 15 |
| 4 | 3 | 12 |
| 5 | 2 | 10 |
| 6 | 6 | 36 |
| 7 | 1 | 7 |
| 8 | 0 | 0 |
| 9 | 5 | 45 |
| 10 | 5 | 50 |
| 11 | 1 | 11 |
| 12 | 3 | 36 |
| SUM | 32 | 224 |

$$\text{average} = \bar{x} = 7$$

$$\text{median} = 6$$

$$\text{mode} = 6$$



Summary Statistics: Variation

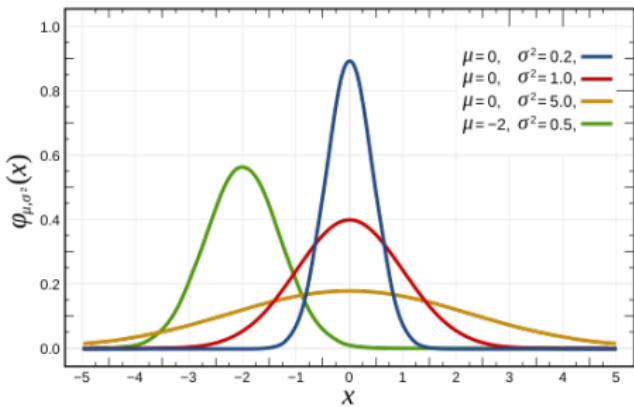
| 1-8 | 9-16 | 17-24 | 25-32 |
|---------------|---------------|----------------|-------------------------|
| 2 3 3 3 3 4 4 | 4 5 5 6 6 6 6 | 6 7 9 9 9 9 10 | 10 10 10 10 11 12 12 12 |

- Interquartile Range (IRQ): Spread of the middle 50% of the data
 - Find the median
 - Find the first quartile (Q1): median of the lower half.
 - Find the third quartile (Q3): median of the upper half.
 - $\text{IRQ} = \text{Q3} - \text{Q1} = 6$
- Standard Deviations (σ):

$$\sigma = \sqrt{\frac{\sum_{i=0}^n (x_i - \bar{x})^2}{n}} = 3.06$$



Gaussian Distribution

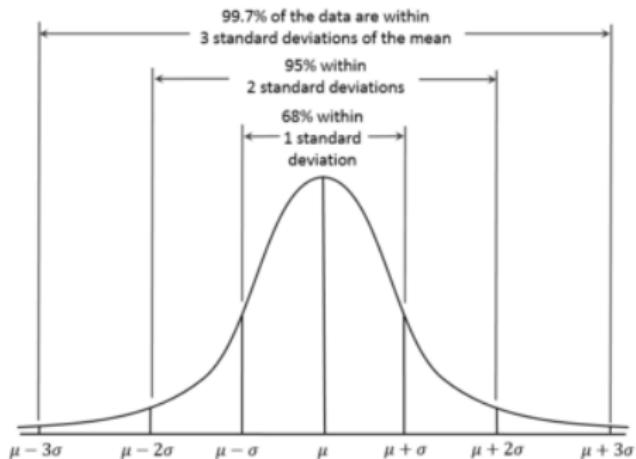


Probability Distribution Function $f(x)$:

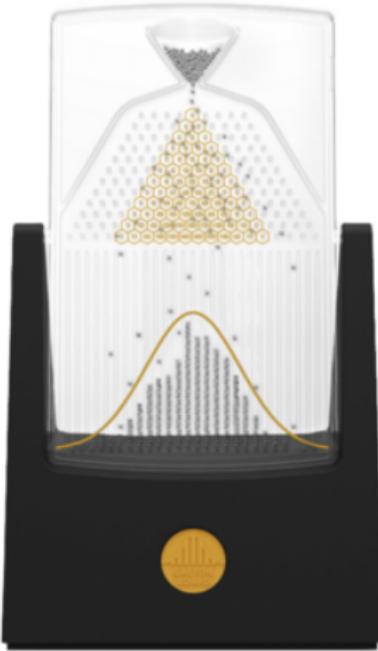
$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\bar{x})^2}{2\sigma^2}}$$



Gaussian Distribution: 3σ

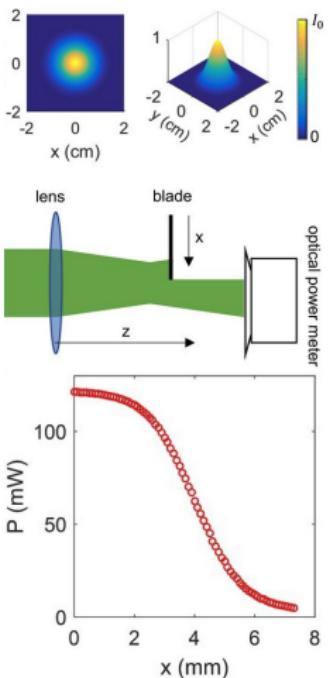


Galton Baord





Assignment: Measuring Bean Profile



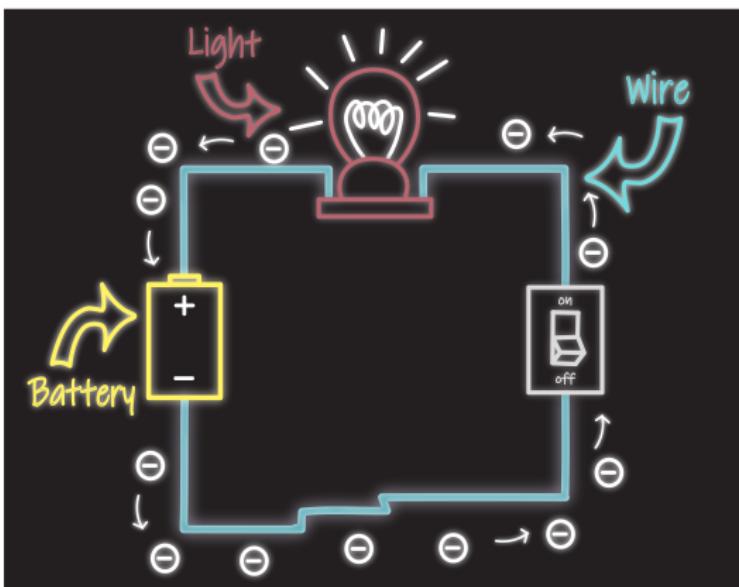
The laser beam has a Gaussian profile.

- ① Direct a laser beam at a power meter, setting the correct wavelength
- ② Moving the knife edge across the beam path, record the drop in power vs distance.
- ③ Setup a telescope to expand the beam size by 2-5 times.
- ④ Repeat the knife edge process.
- ⑤ Plot the results of both sets of measurements on paper and in excel.

Electrical Components and Circuits

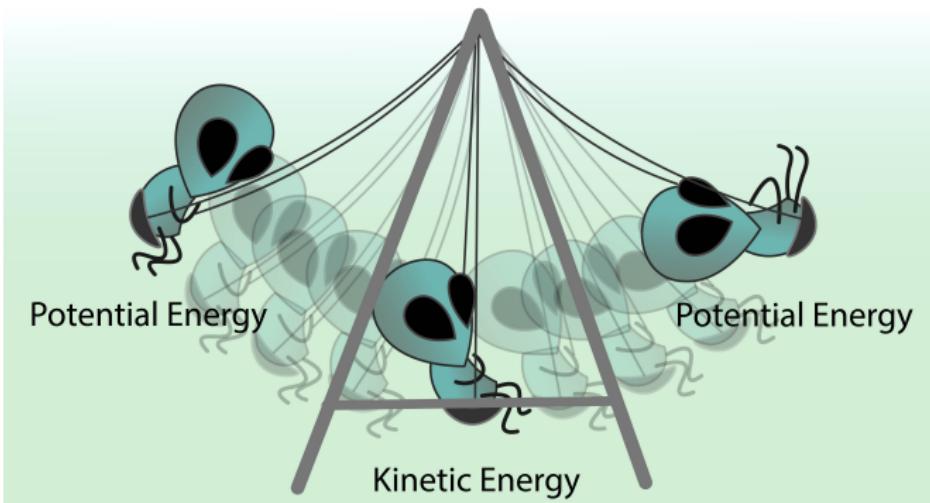


Introduction to Electrical Circuits





Energy



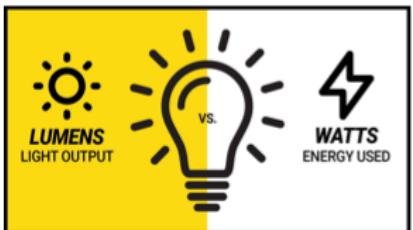
- Kinetic Energy - energy of motion
- Potential Energy - energy stored in an object



Electrical Circuit Terms



Voltage is **electric potential energy per unit charge** ($V = J/C$)

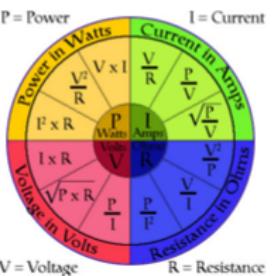


Power is the rate of doing work or **the rate of using energy**. ($W = J/S$)

| The Sub-atomic Particles | | | |
|--------------------------|----------|------------------------|--------------------------|
| Relative size | Name | Mass (Kg) | Charge (C) |
| Proton | Proton | 1.67×10^{-27} | $+1.602 \times 10^{-19}$ |
| Neutron | Neutron | 1.67×10^{-27} | 0 |
| Electron | Electron | 9.11×10^{-31} | -1.602×10^{-19} |



Electric current is the **rate of charge flow** ($A = C/s$)



$$\text{Power} = \text{Voltage} \times \text{Current}$$



Energy is the **amount of power** produced or consumed **over a given time**. ($J = W \times s$)



Measuring Voltage, Current, and Resistance



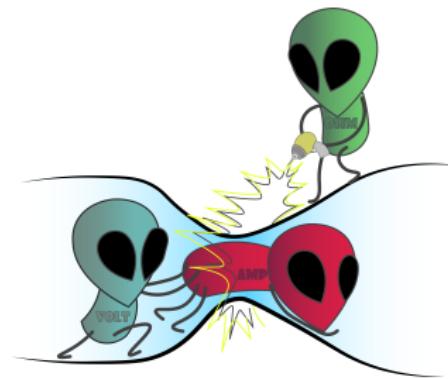
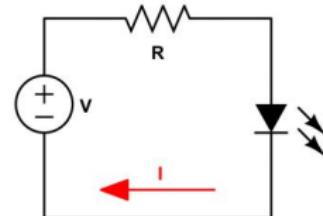


Ohm's Law

Georg Ohm (16 March 1789 – 6 July 1854) was a German physicist and mathematician. As a school teacher, Ohm began his research with the new electrochemical cell, invented by Italian scientist Alessandro Volta. Ohm found that there is a direct proportionality between the potential difference (voltage) applied across a conductor and the resultant electric current. This relationship is known as Ohm's law:

Ohm's Law

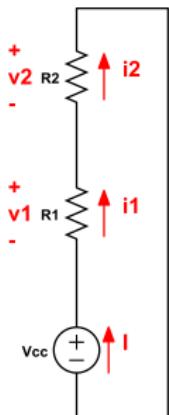
$$V = I * R$$





A word about circuit notation

Subscripts will be used to denote quantities (voltage, current, etc) for different elements:



- i_1 or i_1 is the current through Resistor 1 (R_1)
- i_2 or i_2 is the current through Resistor 2 (R_2)
- v_1 or v_1 is the voltage across Resistor 1 (R_1)
- I is the current delivered by the power supply
- V_{cc} (common collector ^a voltage) is the notation we will use for 3.3V from the Particle

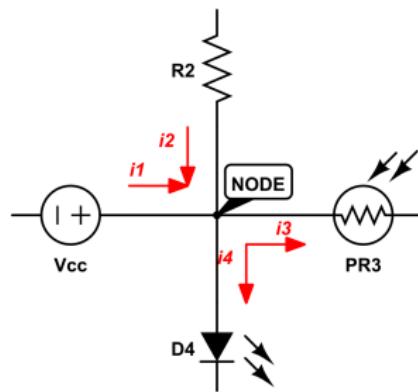
^aCommon Collector is a term for certain parts of transistor circuits. We will learn about Transistors in Lesson 11



Kirchhoff's First Law

Gustav Robert Kirchhoff (12 March 1824 – 17 October 1887) was a German physicist who contributed to the fundamental understanding of electrical circuits. His first law:

In an electrical circuit, the sum of currents flowing into that node is equal to the sum of currents flowing out of that node

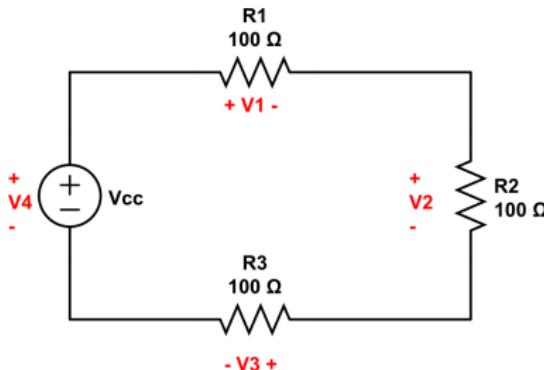


$$i_1 + i_2 = i_3 + i_4$$



Kirchhoff's Second Law

The directed sum of the potential differences (voltages) around any closed loop is zero.



$$V4 - (V1 + V2 + V3) = 0$$

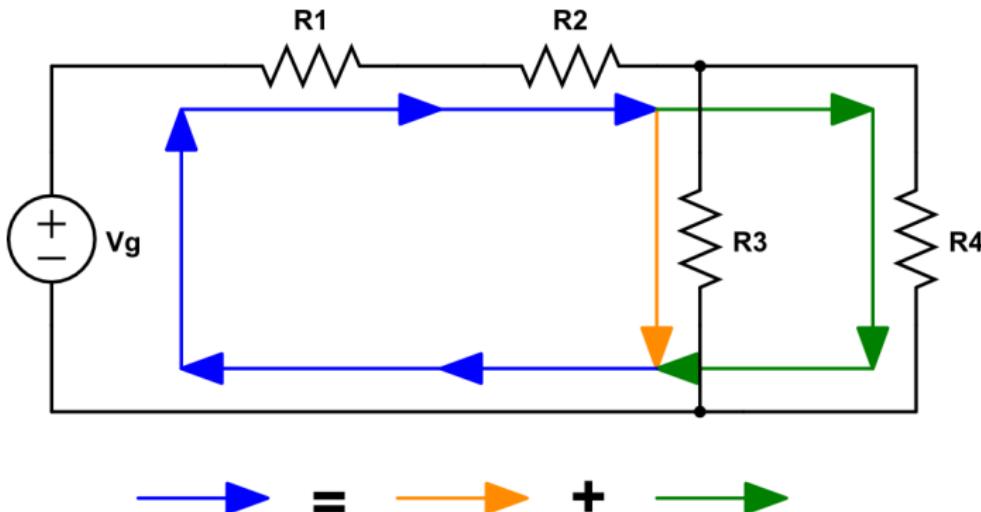


Kirchhoff's Second Law





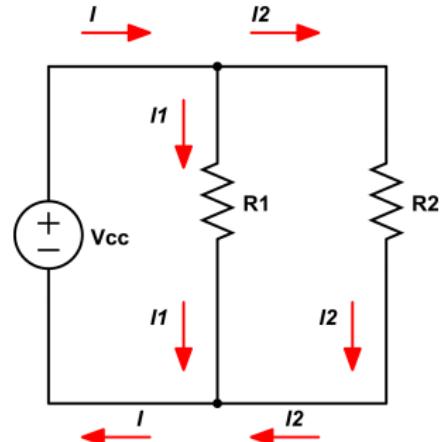
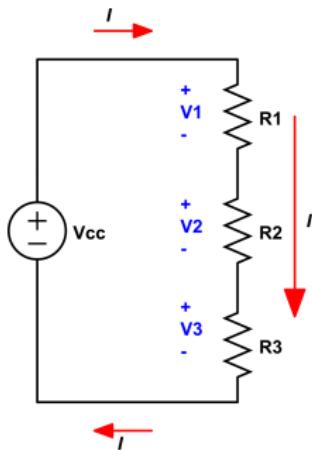
Resistors in Series and Parallel



How many nodes? How many loops?



Resistors in Series and Parallel



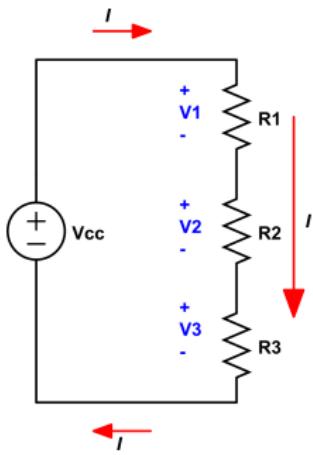
$$R_{eq} = R_1 + R_2 + R_3$$

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2}$$



Resistors in Series

Rearranging the Loop Law:



$$V_{cc} = V_1 + V_2 + V_3 \quad (13)$$

Using Ohm's Law:

$$V_{cc} = IR_1 + IR_2 + IR_3 \quad (14)$$

Using the Distributive Property:

$$V_{cc} = I(R_1 + R_2 + R_3) \quad (15)$$

Node Law: $I = I_1 = I_2 = I_3$

Loop Law:

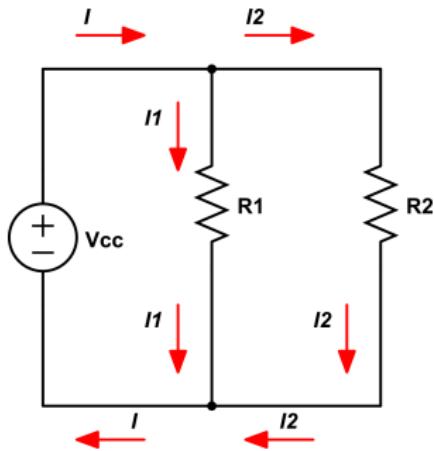
$$V_{cc} - (V_1 + V_2 + V_3) = 0$$

Gives the Equivalent Resistance:

$$R_{eq} = R_1 + R_2 + R_3 \quad (16)$$



Resistors in Parallel



$$I = I_1 + I_2 \quad (17)$$

$$I = \frac{V_1}{R_1} + \frac{V_2}{R_2} \quad (18)$$

$$I = \frac{V_{cc}}{R_1} + \frac{V_{cc}}{R_2} \quad (19)$$

$$\frac{V_{cc}}{R_{eq}} = V_{cc} \left(\frac{1}{R_1} + \frac{1}{R_2} \right) \quad (20)$$

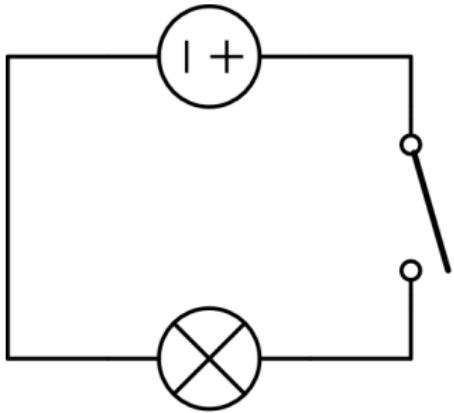
Node Law: $I = I_1 + I_2$

Loop Law: $V_{cc} = V_1 = V_2$

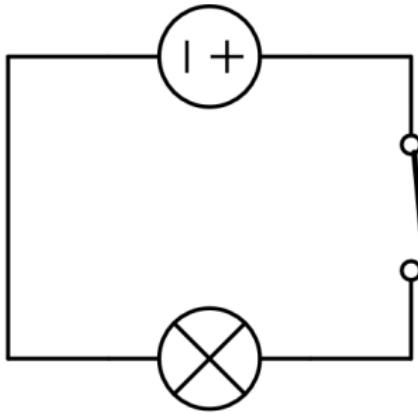
$$\frac{1}{R_{eq}} = \left(\frac{1}{R_1} + \frac{1}{R_2} \right) \quad (21)$$



Switches



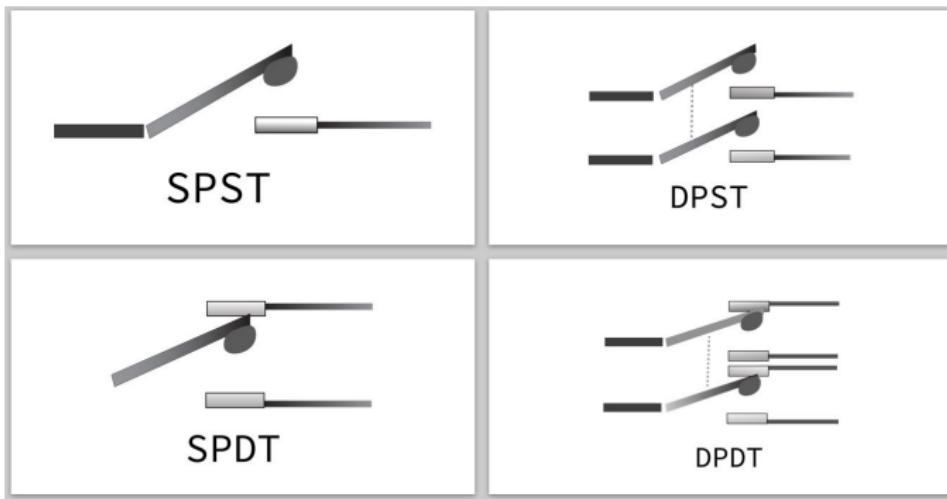
Lamp Off



Lamp On



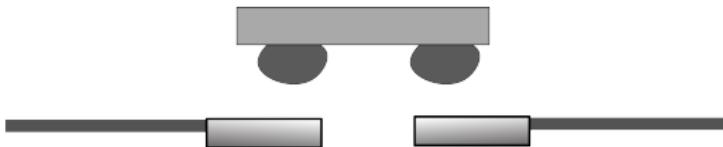
Poles and Throws



- Poles indicates the number of circuits that one switch can control for one operation of the switch.
- Throws indicates the number of contact points.



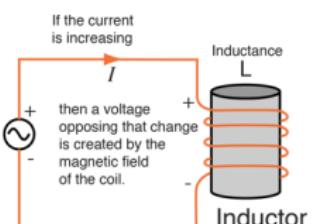
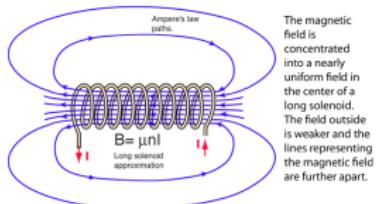
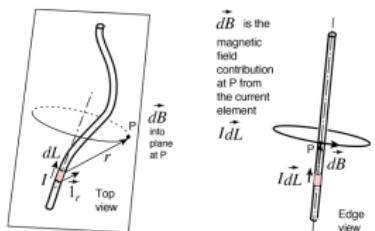
A Button - SPST



SPST
double break



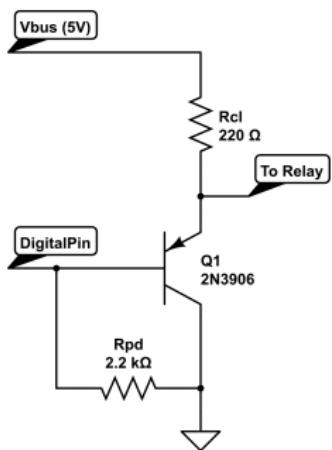
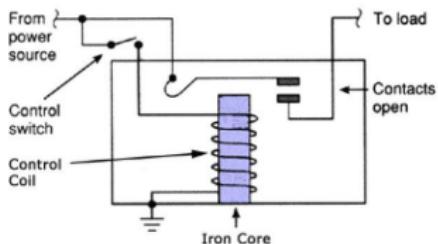
Inductors



- Current flowing in a wire produces a magnetic field (B) around the wire (from Ampere's Law).
- Wire wrapped into a coil produces a magnetic field that resembles a bar magnet through the center of the coil.
- Also, in a coil, this magnetic field produces an effect known as Inductance (L) that opposes changes in electric current.



Relays



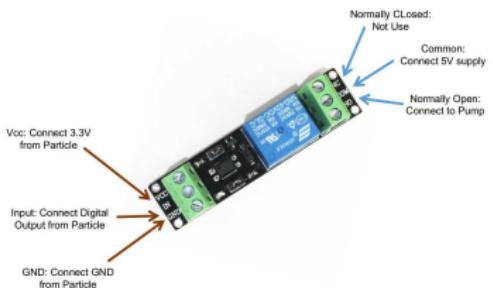
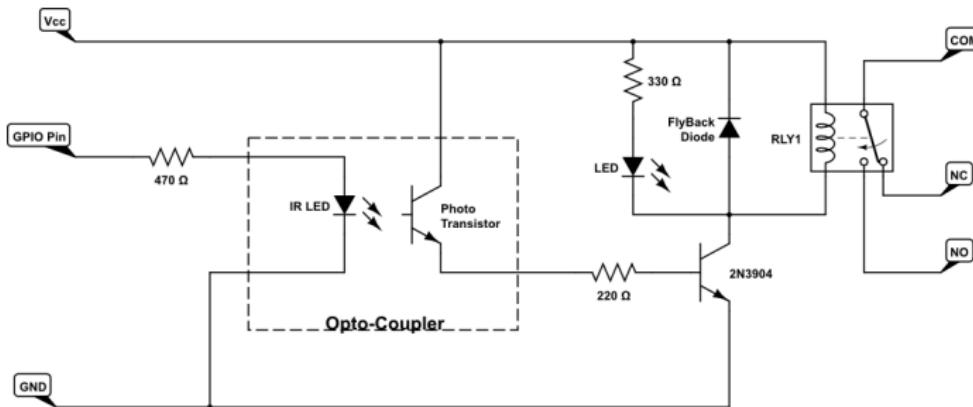
- When a device (e.g. a pump) requires higher voltage ($> 5V$) or higher current, then a relay can be used as a switch for the device

- The relay is activated by a digital pin from the microcontroller.

- As the relay can require as much as 100mA from the digital pin, to provide sufficient current, use a current amplifying emitter follower to draw current directly from the USB connection (V_{BUS}).



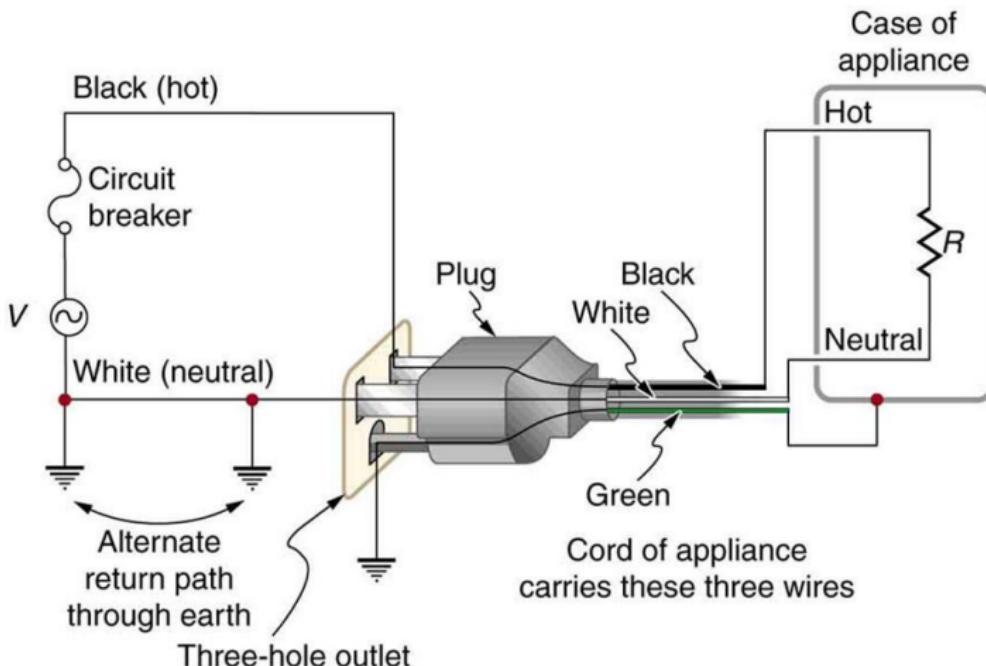
Optocoupled Relay



- Optocoupler isolates the relay load (which could be up to 240V) from the microcontroller electronics.

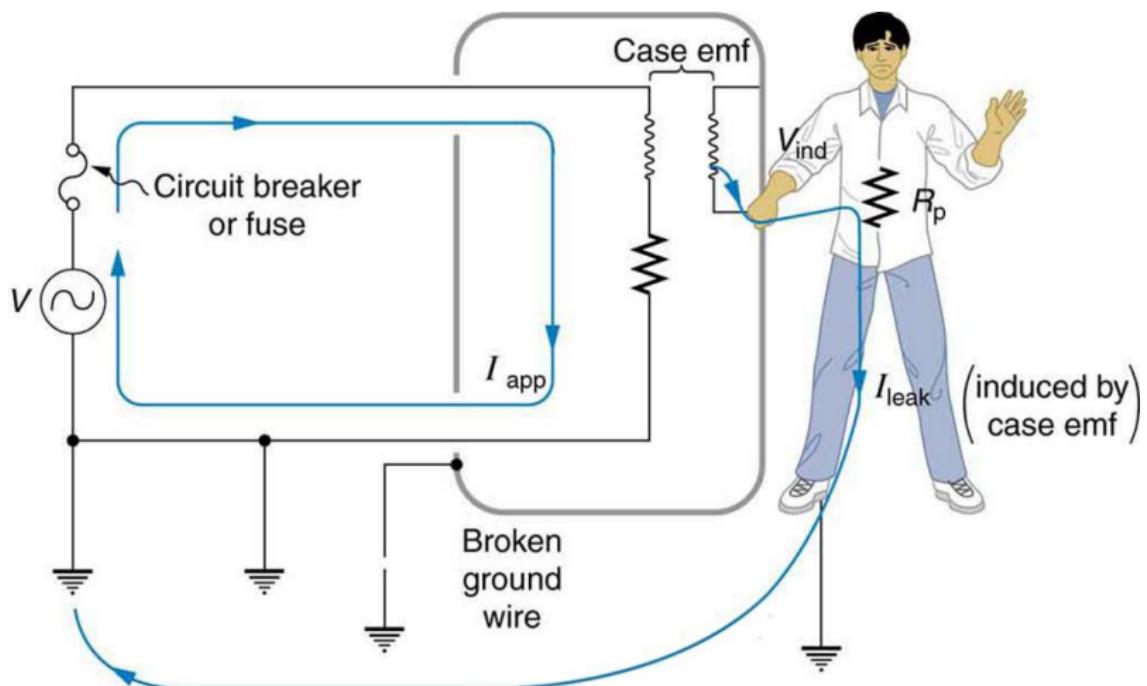


Electrical Safety - Three Wires



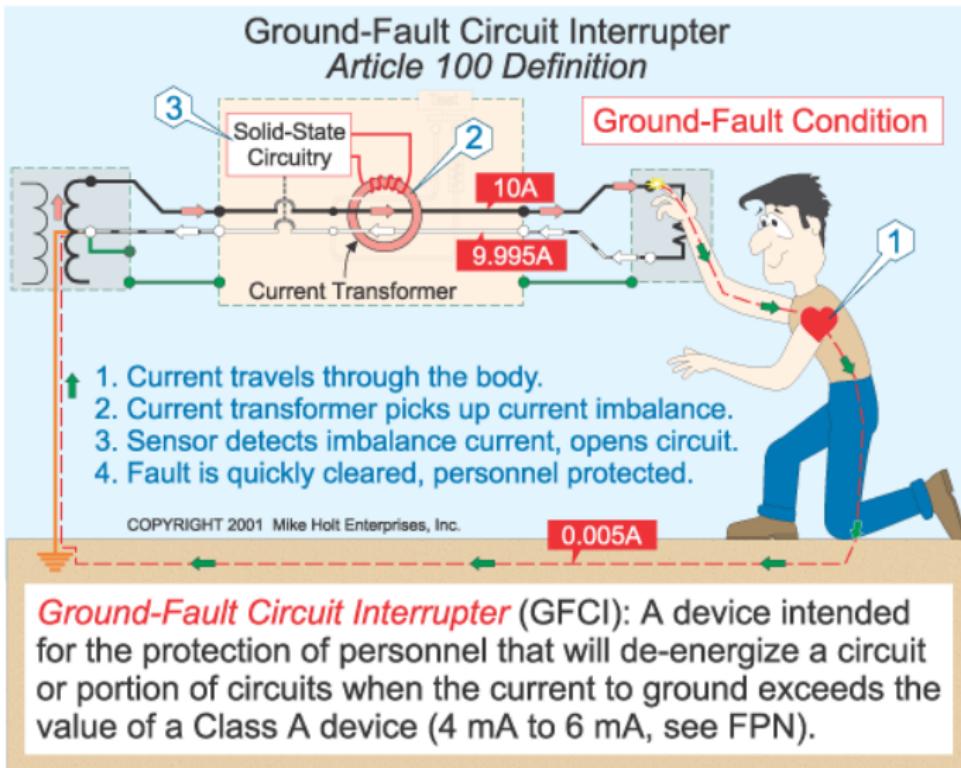


Electrical Safety - Electric Shock





Electrical Safety - GFCI

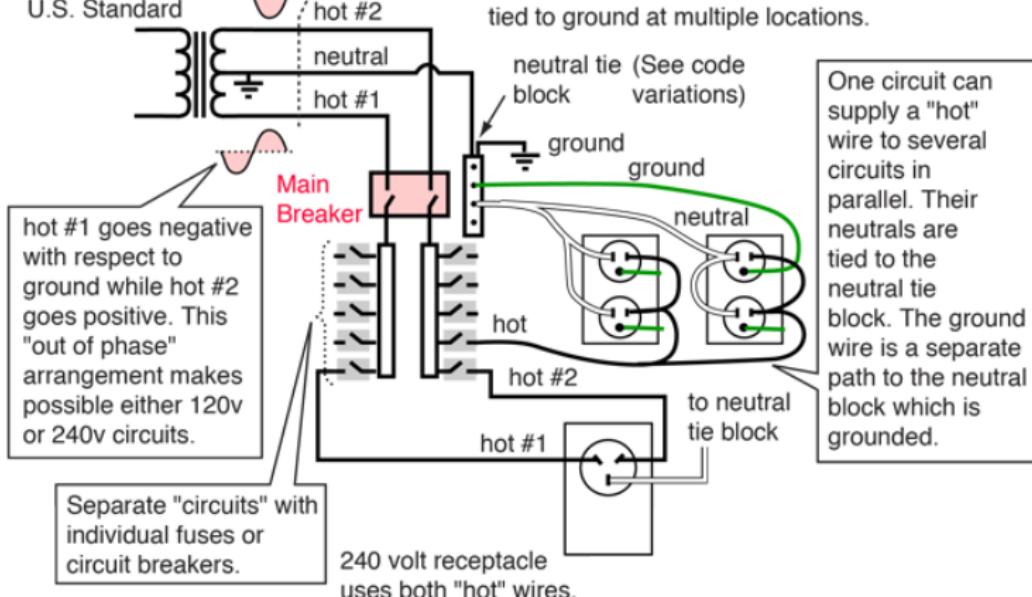




Electrical Safety - 240V

120 volts rms
60 Hz is the
U.S. Standard

Three wires to house: two high voltage or "hot" wires
and a "neutral" return wire which is
tied to ground at multiple locations.



Control Theory



Vescent Laser Servo and Spectroscopy Module



- A laser servo's purpose is to act as a feedback control system to lock a laser's frequency or wavelength to a stable reference.
- Together with the spectroscopy module continuously monitors for any deviations from the target frequency.
- It generates an error signal, calculates a corrective signal using a PID controller and sends it back to the laser to stabilize it



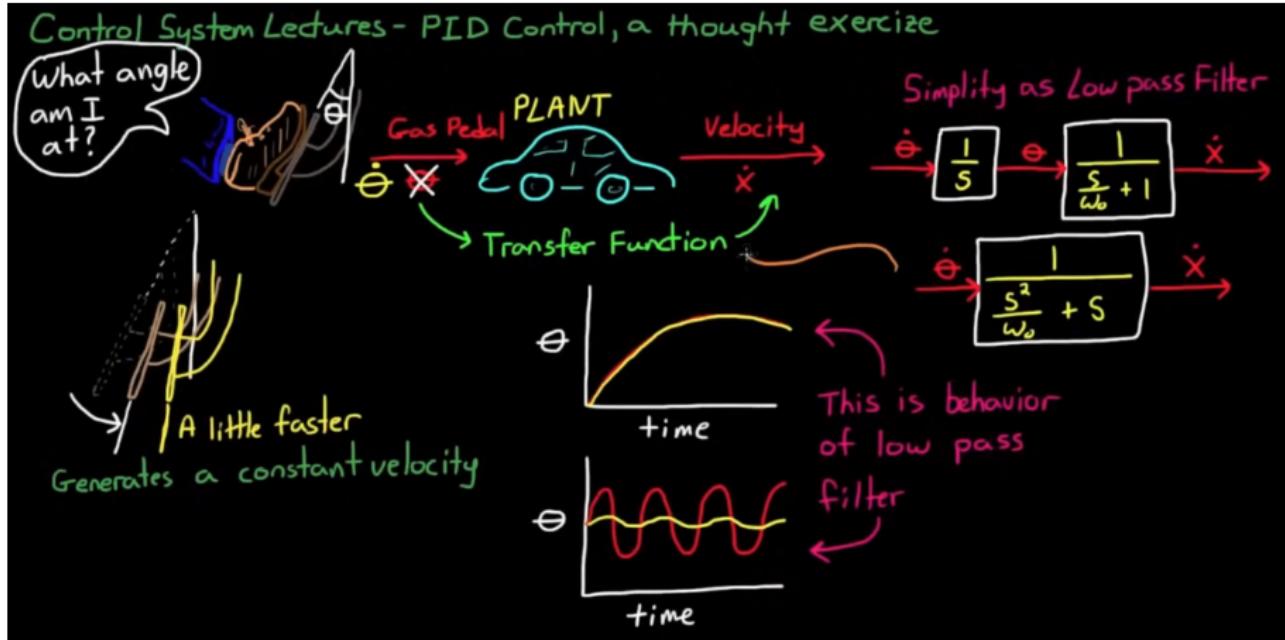
PID Control: Cruise Control Example



<https://youtu.be/XfAt6hNV8XM?si=DFWqnSe2hT0wGM92>



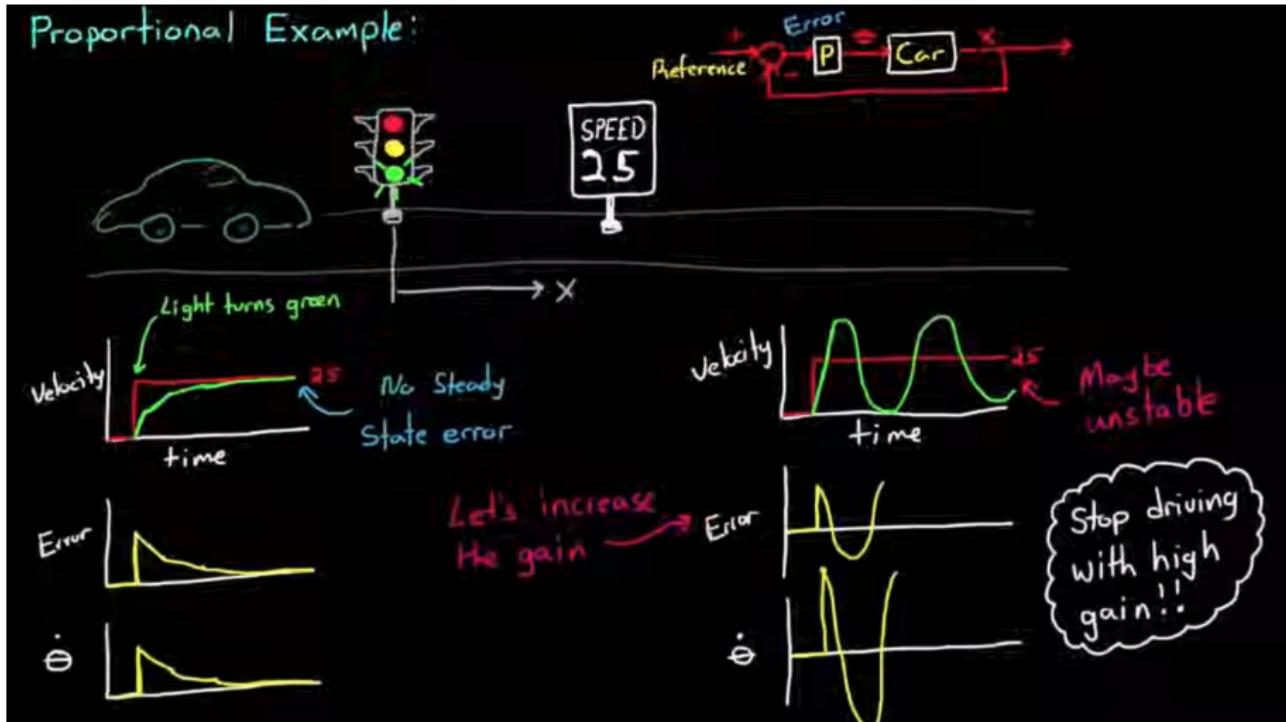
PID Control: The "Plant" (the car)





PID Control: Proportional Control

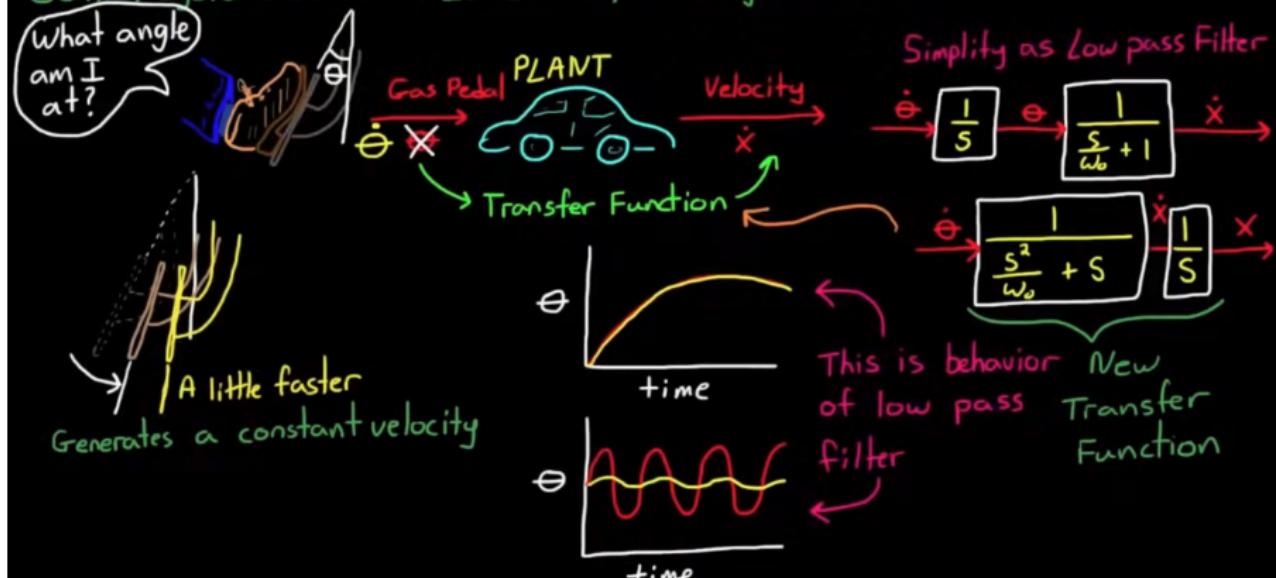
Proportional Example:





PID Control: Proportional Control

Control System Lectures - PID Control, a thought exercise



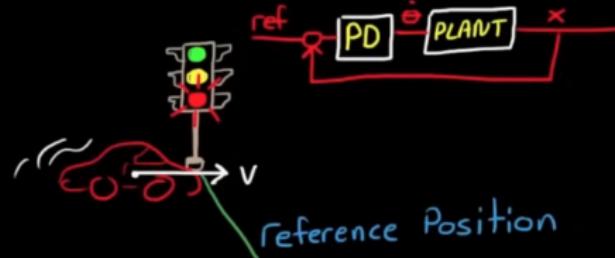
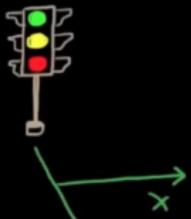
Proportional Example:



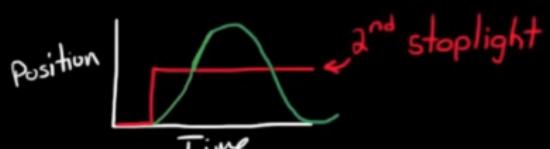


PID Control: Adding in D

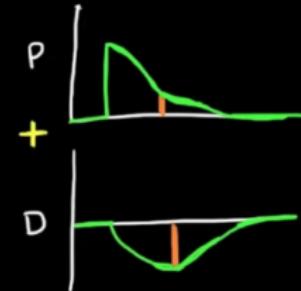
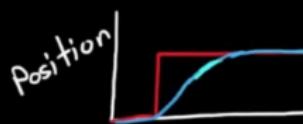
Proportional-Derivative Example



Proportional



PD control





PID Control: Adding in I

Proportional-Derivative-Integral Example



Error

Less error with higher gain



-D
-P

You let go of
the pedal

