

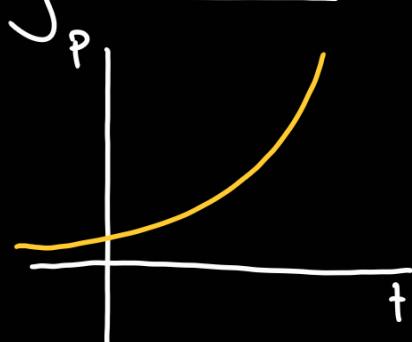
based on "Single Variable Calculus"
by Jonathan D. Rogawski.

Section 7.4.: Exponential growth and decay.

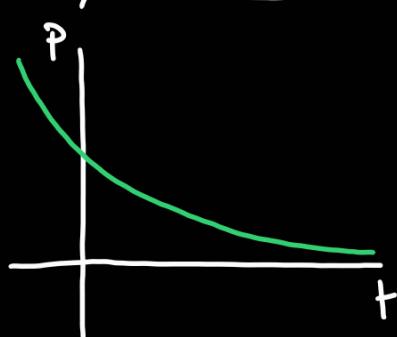
Exponential growth: When a quantity $P(t)$ depends exponentially on time:

$$P(t) = P_0 \cdot e^{kt}$$

growth constant: $k > 0$



decay constant: $k < 0$



To find P_0 , set $t=0$: $P(0) = P_0 \cdot e^{k \cdot 0} = P_0 \cdot e^0 = P_0$.

Example: Population of bacteria. $k = 0.41 \text{ hours}^{-1}$. 1000 bacteria at $t=0$.

a) Find $P(t)$.

$$P_0 = P(0) = 1000 \quad \text{so} \quad P(t) = 1000 \cdot e^{0.41 \cdot t}, \quad t \text{ in hours.}$$

b) How large is the population after 5 hours?

$$P(5) = 1000 \cdot e^{0.41 \cdot 5} \approx 2767.9 \approx 2768.$$

c) When will the population reach 10000?

c) When will the population reach 1000?

$$1000 = P(t) = 1000 \cdot e^{0.41 \cdot t}, \quad e^{0.41 \cdot t} = 10, \quad 0.41 \cdot t = \ln(10),$$

$$t = \frac{\ln(10)}{0.41} \approx 5.62 \text{ hours, } t \text{ is 5 hours and 37 minutes.}$$

The exponential functions are the only functions satisfying the equation:

$$y' = k \cdot y.$$

$$\text{Then } y(t) = P_0 \cdot e^{k \cdot t} \text{ where } P_0 = y(0).$$

y' is the derivative of y , also known as the rate of change.

Example: Penicillin leaves a person's bloodstream at a rate proportional to the amount present.

a) Express this as an equation.

$A(t)$ the quantity of penicillin in the bloodstream at time t .

$A'(t) = -k \cdot A(t)$ with $k > 0$ because $A(t)$ is decreasing.

b) Find the decay constant if 50 mg of penicillin remain in the bloodstream 7 hours after an initial injection of 450 mg.

$A(7) = 50, A(0) = 450, \text{ so:}$

$$A(t) = 450 \cdot e^{-k \cdot t} \quad \text{and} \quad 50 = A(7) = 450 \cdot e^{-k \cdot 7} \text{ gives } k \approx 0.31.$$

c) At what time were 200 mg present?

$$200 = A(t) = 450 \cdot e^{-0.31 \cdot t} \quad \text{so } t \approx 2.62 \text{ hours.}$$

Doubling time: Time T such that $P(t)$ doubles in size: $P(t+T) = 2 \cdot P(t)$.

$$P(t) = P_0 \cdot e^{k \cdot t}, k > 0, \text{ then:}$$

$$T = \frac{\ln(2)}{k}$$

Example: Spread of a virus. $k = 0.0815 \text{ s}^{-1}$.

a) What is the doubling time?

$$T = \frac{\ln(2)}{0.0815} \approx 8.5 \text{ seconds.}$$

b) If the virus began in four individuals, how many hosts were infected after 2 minutes? And after 3 minutes?

$$P_0 = P(0) = 4, \quad P(t) = 4 \cdot e^{0.0815 \cdot t}, \quad 2 \text{ min} = 120 \text{ seconds}$$

$$P(120) = 4 \cdot e^{0.0815 \cdot 120} \approx 70200. \quad 3 \text{ min} = 180 \text{ seconds}$$

$$P(180) = 4 \cdot e^{0.0815 \cdot 180} \approx 940000.$$

Half-life: Time T such that $P(t)$ halves in size: $P(t+T) = \frac{1}{2} \cdot P(t)$.

$$P(t) = P_0 \cdot e^{-k \cdot t}, k > 0, \text{ then:}$$

$$T = \frac{\ln(2)}{k}$$

Example: An isotope decays with a half life of 3.825 days. How long will it take for 80% of the isotope to decay?

$$R(t) = R_0 \cdot e^{-kt}, \quad 3.825 = \frac{\ln(2)}{k} \quad \text{so} \quad k = \frac{\ln(2)}{3.825} \approx 0.181.$$

$R_0 = R(0)$ is the initial amount. When 80% has decayed, 20% remains,

$$\text{so } R(t) = 0.2 \cdot R_0 : \quad R_0 \cdot e^{-0.181 \cdot t} = 0.2 \cdot R_0, \quad t = \frac{\ln(0.2)}{-0.181} \approx 8.9 \text{ days.}$$

Remark: The formulas for the doubling time and the half-life are

the same. For the doubling time we solve:

$$P(t+T) = 2 \cdot P(t) \quad \text{with } P(t) = P_0 \cdot e^{kt}, \quad k > 0.$$

$$P_0 \cdot e^{k \cdot (t+T)} = 2 \cdot P_0 \cdot e^{kt} \quad \text{so} \quad e^{k \cdot (t+T)} = 2 \cdot e^{kt}.$$

For the half-life we solve:

$$P(t+T) = \frac{1}{2} \cdot P(t) \quad \text{with } P(t) = P_0 \cdot e^{-kt}, \quad k > 0$$

$$P_0 \cdot e^{-k \cdot (t+T)} = \frac{1}{2} \cdot P_0 \cdot e^{-kt} \quad \text{so} \quad \frac{1}{e^{k \cdot (t+T)}} = \frac{1}{2} \cdot \frac{1}{e^{kt}}$$

and the remaining equation is: $2 \cdot e^{kt} = e^{k \cdot (t+T)}$, the same

equation as for the doubling time.

Section 7.1: Derivative of $f(x) = b^x$ and the number e .

Exponential function: $f(x) = b^x$ with base $b > 0$ and $b \neq 1$.

1. They are always strictly positive.

2. Their range is all the positive real numbers.

3. Increasing if $b > 1$ and decreasing if $0 < b < 1$.

Laws of exponents:

Exponent zero	$b^0 = 1$
Products	$b^x \cdot b^y = b^{x+y}$
Quotients	$\frac{b^x}{b^y} = b^{x-y}$
Negative exponents	$b^{-x} = \frac{1}{b^x}$
Power to a power	$(b^x)^y = b^{xy}$
Roots	$b^{\frac{1}{n}} = \sqrt[n]{b}$

Example: Simplify:

$$a) 16^{-\frac{1}{2}} = \frac{1}{16^{\frac{1}{2}}} = \frac{1}{\sqrt{16}} = \frac{1}{4}.$$

$$b) 27^{\frac{2}{3}} = (27^{\frac{1}{3}})^2 = (\sqrt[3]{27})^2 = 3^2 = 9.$$

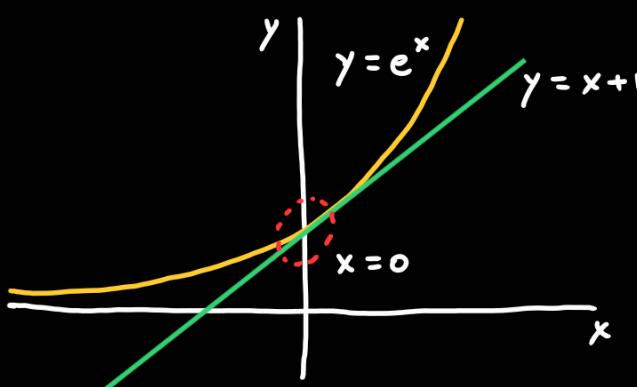
$$c) 4^{16} \cdot 4^{-18} = 4^{-2} = \frac{1}{4^2} = \frac{1}{16}.$$

$$d) \frac{9^3}{3^7} = \frac{(3^2)^3}{3^7} = \frac{3^6}{3^7} = 3^{-1} = \frac{1}{3}.$$

Derivative of the exponential function:

$$\frac{d}{dx}(b^x) = \ln(b) \cdot b^x$$

There is a unique positive real number e such that $\frac{d}{dx}(e^x) = e^x$



At $x=0$, the tangent line to e^x has slope $m=1$.

Example: Find the equation of the tangent line to $3e^x - 5x^2$ at $x=2$.

For $f(x) = 3e^x - 5x^2$ we have:

$$f'(x) = 3 \cdot \frac{d}{dx}(e^x) - 5 \cdot \frac{d}{dx}(x^2) = 3 \cdot e^x - 10 \cdot x,$$

$$f(2) = 3e^2 - 5 \cdot (2^2) \approx 2.17$$

$$f'(2) = 3e^2 - 10 \cdot 2 \approx 2.17$$

So the tangent line is $y = f(2) + f'(2) \cdot (x-2) \approx 2.17 \cdot (x-1)$.

Using the chain rule for derivatives (with k and b constant):

$$\boxed{\frac{d}{dx}(e^{g(x)}) = g'(x) \cdot e^{g(x)} \quad \text{and} \quad \frac{d}{dx}(e^{kx+b}) = k \cdot e^{kx+b}}$$

Example: Differentiate:

a) $\frac{d}{dx}(e^{9x-5}) = 9 \cdot e^{9x-5}$

b) $\frac{d}{dx}(e^{\cos(x)}) = -(\sin(x)) \cdot e^{\cos(x)}$

Integral of the exponential function: (with k and b constant, $k \neq 0$)

$$\int e^x \cdot dx = e^x + C_1 \quad \text{and} \quad \int e^{kx+b} \cdot dx = \frac{1}{k} \cdot e^{kx+b} + C_1$$

Example: Evaluate:

$$a) \int e^{7x-5} \cdot dx = \frac{1}{7} \cdot e^{7x-5} + C_1.$$

$$b) \int x \cdot e^{2x^2} \cdot dx = \frac{1}{4} \int e^u du = \frac{1}{4} e^u + C_1 = \frac{1}{4} e^{2x^2} + C_1.$$

\uparrow
 $u = 2x^2$
 $du = 4x dx$

$$c) \int \frac{e^t}{1+2e^t+e^{2t}} \cdot dt = \int \frac{e^t}{(1+e^t)^2} \cdot dt = \int \frac{du}{(1+u)^2} = -(1+u)^{-1} + C_1 =$$

\uparrow
 $u = e^t$
 $du = e^t dt$

$$= -(1+e^t)^{-1} + C_1.$$

Section 7.2.: Inverse functions.

The inverse of $f(x)$, is the function that reverses $f(x)$.

Let $f(x)$ have domain D and range R . If there is a function $g(x)$ with domain R such that $g(f(x)) = x$ for all $x \in D$ and $f(g(x)) = x$ for all $x \in R$ then $f(x)$ is said to be invertible. We call $g(x)$ the inverse, and is denoted $f^{-1}(x)$.

Example: Find the inverse of $f(x) = 2x - 18$.

Step 1: Solve $y = f(x)$ for x in terms of y .

$$y = 2x - 18 \quad \text{so} \quad y + 18 = 2x \quad \text{so} \quad x = \frac{y}{2} + 9.$$

Thus $f^{-1}(y) = \frac{y}{2} + 9$.

Step 2: Rewrite with x instead of y . $f^{-1}(x) = \frac{x}{2} + 9$.

Step 3: Check $f^{-1}(f(x)) = x$ and $f(f^{-1}(x)) = x$.

$$f^{-1}(f(x)) = f^{-1}(2x - 18) = \frac{2x - 18}{2} + 9 = x - 9 + 9 = x.$$

$$f(f^{-1}(x)) = f\left(\frac{x}{2} + 9\right) = 2 \cdot \left(\frac{x}{2} + 9\right) - 18 = x + 18 - 18 = x.$$

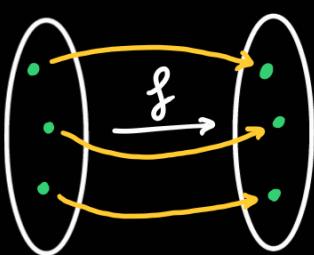
If $f^{-1}(x)$ exists, it is unique. However, some functions like $f(x) = x^2$

do not have an inverse. When is a given function invertible?

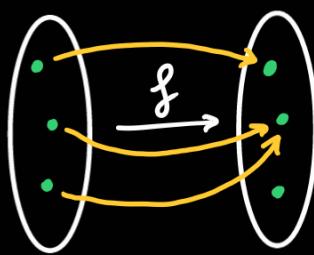
A function $f(x)$ is one-to-one on a domain D if for every $c \in D$ the equation $f(x) = c$ has at most one solution $x \in D$.

Equivalently, if $f(a) = f(b)$ then $a = b$.

one-to-one:



not one-to-one:



This is a function f if f^{-1} is a function if f is one-to-one.

The inverse function $f^{-1}(x)$ exists if and only if $f(x)$ is one-to-one on its domain D . Then the domain of f is the range of f^{-1} , and the range of f is the domain of f^{-1} .

Example: Find the inverse of $f(x) = \frac{3x+2}{5x-1}$.

The domain of $f(x)$ is $D = \{x \mid x \neq \frac{1}{5}\}$. For $x \in D$, solve $y = f(x)$ for x .

$$y = \frac{3x+2}{5x-1} \quad \text{so} \quad (5x-1)y = 3x+2 \quad \text{so} \quad 5xy - y = 3x + 2 \quad \text{so}$$

$$5xy - 3x = y + 2 \quad \text{so} \quad x(5y - 3) = y + 2 \quad \text{so} \quad x = \frac{y+2}{5y-3}$$

whenever $y \neq \frac{3}{5}$. However $y = \frac{3}{5}$ is not in the range of $f(x)$ since

otherwise $x(5y-3) = y+2$ gives $0 = \frac{3}{5} + 2$, which is false.

Since $x = \frac{y+2}{5y-3}$, for each $y \neq \frac{3}{5}$ there is a unique x with $f(x) = y$.

So $f(x)$ is one-to-one on its domain, so it is invertible. The range

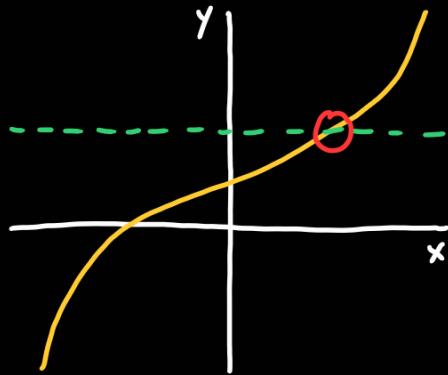
of $f(x)$ is $R = \{x \mid x \neq \frac{3}{5}\}$ and $f^{-1}(x) = \frac{x+2}{5x-3}$, which has range D

and domain R .

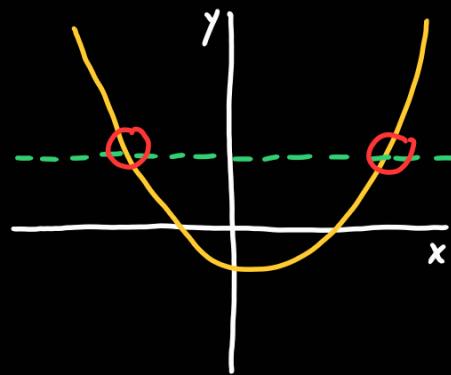
Horizontal line test: A function $f(x)$ is one-to-one if and only if every

horizontal line intersects the graph of $f(x)$ in at most one point.

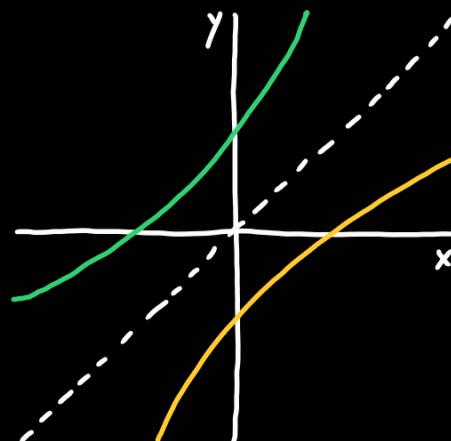
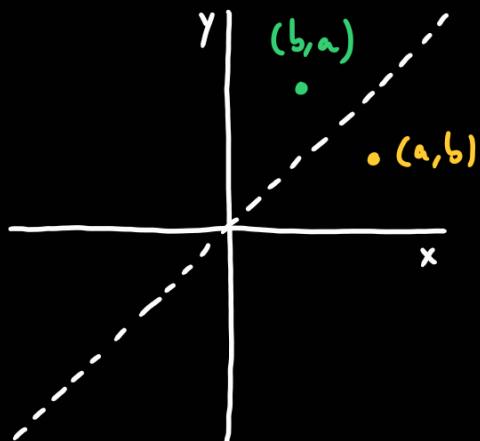
one-to-one:



not one-to-one:



The graph of f^{-1} is the reflection of the graph of f through $y=x$.



Derivative of the inverse:

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

$f(x)$ differentiable and one-to-one, b in domain of $f^{-1}(x)$, $f'(f^{-1}(b)) \neq 0$.

Example: Calculate $(f^{-1}(x))'$ for $f(x) = x^4 + 10$ on $D = \{x | x \geq 0\}$.

Solve $y = x^4 + 10$ for x to obtain $x = (y-10)^{\frac{1}{4}}$, so $f^{-1}(x) = (x-10)^{\frac{1}{4}}$.

Now $f'(x) = 4x^3$ so $f'(f^{-1}(x)) = 4 \cdot (f^{-1}(x))^3 = 4 \cdot (x-10)^{\frac{3}{4}}$ so:

$$(f^{-1}(x))' = \frac{1}{f'(f^{-1}(x))} = \frac{1}{4 \cdot (x-10)^{\frac{3}{4}}} = \frac{(x-10)^{-\frac{3}{4}}}{4}.$$

If we directly differentiate $f(x)$ we also obtain this.

Section 7.3.: Logarithms and their derivatives.

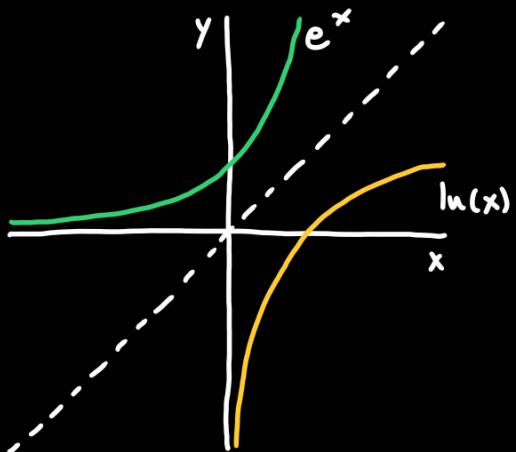
Logarithms are inverses of exponentials.

$$\boxed{b^{\log_b(x)} = x \quad \text{and} \quad \log_b(b^x) = x}$$

Thus $\log_b(x)$ is the number to which b must be raised to get x .

1. The domain of $\log_b(x)$ is $\{x | x > 0\}$.

2. The range of $\log_b(x)$ is all real numbers.



If $b > 1$ then $\log_b(x) > 0$ for $x > 1$, $\log_b(x) < 0$ for $x < 1$, and:

$$\lim_{x \rightarrow 0^+} \log_b(x) = -\infty, \quad \lim_{x \rightarrow \infty} \log_b(x) = \infty$$

Laws of logarithms:

$$\begin{array}{ll} \text{Log of 1} & \log_b(1) = 0 \end{array}$$

$$\begin{array}{ll} \text{Log of } b & \log_b(b) = 1 \end{array}$$

Products

$$\log_b(x \cdot y) = \log_b(x) + \log_b(y)$$

Quotients

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

Reciprocals

$$\log_b\left(\frac{1}{x}\right) = -\log_b(x)$$

Powers

$$\log_b(x^u) = u \cdot \log_b(x)$$

Change of base:

$$\log_b(x) = \frac{\log_a(x)}{\log_a(b)}, \quad \log_b(x) = \frac{\ln(x)}{\ln(b)}$$

Example: Evaluate:

a) $\log_6(9) + \log_6(4) = \log_6(9 \cdot 4) = \log_6(36) = \log_6(6^2) = 2$.

b) $\ln\left(\frac{1}{e^{\frac{1}{2}}}\right) = \ln(e^{-\frac{1}{2}}) = -\frac{1}{2} \ln(e) = -\frac{1}{2}$.

c) $10 \cdot \log_b(b^3) - 4 \cdot \log_b(\sqrt{b}) = 10 \cdot 3 - 4 \cdot \log_b(b^{\frac{1}{2}}) = 30 - 4 \cdot \frac{1}{2} = 28$.

Derivative of the exponential function:

$$\frac{d}{dx}(b^x) = \ln(b) \cdot b^x$$

Example: Differentiate:

a) $\frac{d}{dx}(4^{3x}) = \frac{d}{du}(4^u) \cdot \frac{d}{dx}(u) = \ln(4) \cdot 4^u \cdot 3 = 3 \cdot \ln(4) \cdot 4^{3x}$

\uparrow
 $u = 3x$
 $du = 3 dx$

b) $\frac{d}{dx}(5^{x^2}) = \frac{d}{du}(5^u) \cdot \frac{d}{dx}(u) = \ln(5) \cdot 5^u \cdot 2 \cdot x = 2 \cdot \ln(5) \cdot x \cdot 5^{x^2}$

\uparrow

$$u = x^2$$

$$du = 2x \, dx$$

Derivative of the natural logarithm:

$$\frac{d}{dx} (\ln(x)) = \frac{1}{x}, \quad x > 0$$

Example: Differentiate:

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

$$b) \frac{d}{dx} (\ln(x^2)) = 2 \cdot \ln(x) \cdot \frac{d}{dx} (\ln(x)) = \frac{2 \cdot \ln(x)}{x}.$$

Derivative of log composite:

$$\frac{d}{dx} (\ln(f(x))) = \frac{f'(x)}{f(x)}$$

Example: Differentiate:

$$a) \frac{d}{dx} (\ln(x^3 + 1)) = \frac{3x^2}{x^3 + 1}.$$

$$b) \frac{d}{dx} (\ln(\sqrt{\sin(x)})) = \frac{d}{dx} (\ln(\sin(x)^{\frac{1}{2}})) = \frac{1}{2} \cdot \frac{d}{dx} (\ln(\sin(x))) =$$

$$= \frac{\cos(x)}{2 \cdot \sin(x)}$$

$$c) \frac{d}{dx} (\log_{10}(x)) = \frac{d}{dx} \left(\frac{\ln(x)}{\ln(10)} \right) = \frac{1}{\ln(10)} \cdot \frac{d}{dx} (\ln(x)) = \frac{1}{\ln(10) \cdot x}.$$

$$d) \frac{d}{dx} \left(\frac{(x+1)^2 \cdot (2x^2 - 3)}{\sqrt{x^2 + 1}} \right) = \frac{\frac{d}{dx} (f(x) \cdot g(x)) \cdot h(x) - f(x) \cdot g(x) \cdot \frac{d}{dx} (h(x))}{h(x)^2} =$$

$$f(x) = (x+1)^2, \quad g(x) = 2x^2 - 3, \quad h(x) = \sqrt{x^2 + 1}.$$

$$f'(x) = 2(x+1), \quad g'(x) = 4x, \quad h'(x) = \frac{x}{\sqrt{x^2 + 1}}$$

$$(f'(x) \cdot g(x) + f(x) \cdot g'(x)) \cdot h(x) - f(x) \cdot g(x) \cdot h'(x)$$

$$h(x)^2 = \frac{6x^5 + 8x^4 + 7x^3 + 12x^2 + x - 6}{(x^2+1)^{\frac{3}{2}}}.$$

Logarithmic differentiation: Differentiate $\ln(f(x))$:

$$\begin{aligned}\ln(f(x)) &= \ln((x+1)^2) + \ln(2x^2-3) - \ln(\sqrt{x^2+1}) = \\ &= 2 \cdot \ln(x+1) + \ln(2x^2-3) - \frac{1}{2} \cdot \ln(x^2+1)\end{aligned}$$

Then:

$$\begin{aligned}\frac{f'(x)}{f(x)} &= \frac{d}{dx}(\ln(f(x))) = 2 \cdot \frac{d}{dx}(\ln(x+1)) + \frac{d}{dx}(\ln(2x^2-3)) - \frac{1}{2} \cdot \frac{d}{dx}(\ln(x^2+1)) = \\ &= \frac{2}{x+1} + \frac{4x}{2x^2-3} - \frac{1}{2} \cdot \frac{2x}{x^2+1}\end{aligned}$$

So multiplying by $f(x)$:

$$\begin{aligned}f'(x) &= \left(\frac{(x+1)^2 \cdot (2x^2-3)}{\sqrt{x^2+1}} \right) \cdot \left(\frac{2}{x+1} + \frac{4x}{2x^2-3} - \frac{x}{x^2+1} \right) = \\ &= \frac{6x^5 + 8x^4 + 7x^3 + 12x^2 + x - 6}{(x^2+1)^{\frac{3}{2}}}.\end{aligned}$$

Section 7.7.: L'Hôpital's rule.

L'Hôpital's rule is a tool for computing limits and determining "asymptotic behavior"; that is, limits at infinity.

L'Hôpital's rule: Assume that $f(x)$ and $g(x)$ are differentiable around a and

that $f(a) = 0 = g(a)$. Assume also that $g'(x) \neq 0$ except possibly at $x=a$.

Then if the limit exists:

$$\boxed{\lim_{x \rightarrow a} \frac{f(x)}{g(x)} = \lim_{x \rightarrow a} \frac{f'(x)}{g'(x)}}.$$

This also holds if $\lim_{x \rightarrow a} f(x) = \pm\infty$ and $\lim_{x \rightarrow a} g(x) = \pm\infty$, and it is valid for one-sided limits.

Example: Evaluate:

$$\lim_{x \rightarrow 2} \frac{x^3 - 8}{x^4 + 2x - 20} = \lim_{x \rightarrow 2} \frac{3x^2}{4x^3 + 2} = \frac{3 \cdot 4}{4 \cdot 8 + 2} = \frac{12}{34} = \frac{6}{17}.$$

$$f(x) = x^3 - 8 \quad f(2) = 0$$

$$g(x) = x^4 + 2x - 20 \quad g(2) = 0 \quad g'(x) = 4x^3 + 2 \text{ is not zero near } x=2$$

Example: Evaluate:

$$\lim_{x \rightarrow 2} \frac{4 - x^2}{\sin(\pi x)} = \lim_{x \rightarrow 2} \frac{-2x}{\pi \cdot \cos(\pi x)} = \frac{-2 \cdot 2}{\pi \cdot \cos(2\pi)} = -\frac{4}{\pi}.$$

$$f(x) = 4 - x^2 \quad f(2) = 0$$

$$g(x) = \sin(\pi x) \quad g(2) = 0 \quad g'(x) = \pi \cdot \cos(\pi x) \text{ is not zero near } x=2.$$

Example: Evaluate:

$$\lim_{x \rightarrow \frac{\pi}{2}} \frac{\cos^2(x)}{1 - \sin(x)} = \lim_{x \rightarrow \frac{\pi}{2}} \frac{-2 \cdot \sin(x) \cdot \cos(x)}{-\cos(x)} = \lim_{x \rightarrow \frac{\pi}{2}} 2 \cdot \sin(x) = 2.$$

$$f(x) = \cos^2(x) \quad f\left(\frac{\pi}{2}\right) = 0$$

$$g(x) = 1 - \sin(x) \quad g\left(\frac{\pi}{2}\right) = 0 \quad g'(x) = -\cos(x) \text{ is not zero near } x=\frac{\pi}{2}.$$

Example: Evaluate:

$$\lim_{x \rightarrow 0^+} x \cdot \ln(x) = \lim_{x \rightarrow 0^+} \frac{\ln(x)}{\frac{1}{x}} = \lim_{x \rightarrow 0^+} \frac{\frac{1}{x}}{-\frac{1}{x^2}} = \lim_{x \rightarrow 0^+} -x = 0.$$

$$f(x) = x$$

$$g(x) = \ln(x)$$

$$f(x) \rightarrow 0$$

$$g(x) \rightarrow -\infty$$

$$f(x) = \frac{1}{x}$$

$$g(x) = \ln(x)$$

L'Hôpital's Rule applies.

Example: Evaluate:

$$\lim_{x \rightarrow 0} \frac{e^x - x - 1}{\cos(x) - 1} = \lim_{x \rightarrow 0} \frac{e^x - 1}{-\sin(x)} = \lim_{x \rightarrow 0} \frac{e^x}{-\cos(x)} = -1.$$

$$f(x) = e^x - x - 1$$

$$g(x) = \cos(x) - 1$$

$$f(x) = e^x - 1$$

$$g(x) = -\sin(x)$$

Example: Evaluate:

$$\begin{aligned} \lim_{x \rightarrow 0} \left(\frac{1}{\sin(x)} - \frac{1}{x} \right) &= \lim_{x \rightarrow 0} \frac{x - \sin(x)}{x \cdot \sin(x)} = \lim_{x \rightarrow 0} \frac{1 - \cos(x)}{x \cdot \cos(x) + \sin(x)} = \\ &\quad \uparrow \qquad \qquad \qquad \uparrow \\ &\quad f(x) = x - \sin(x) \qquad \qquad f(x) = 1 - \cos(x) \\ &\quad g(x) = x \cdot \sin(x) \qquad \qquad g(x) = x \cdot \cos(x) - \sin(x) \\ &= \lim_{x \rightarrow 0} \frac{\sin(x)}{-x \cdot \sin(x) + 2 \cdot \cos(x)} = 0. \end{aligned}$$

Example: Evaluate:

$$\lim_{x \rightarrow 0^+} x^x = \lim_{x \rightarrow 0^+} e^{\ln(x^x)} = e^{\lim_{x \rightarrow 0^+} \ln(x^x)} = e^0 = 1$$

$f(x) = e^x$ is continuous

* $\lim_{x \rightarrow 0^+} \ln(x^x) = \lim_{x \rightarrow 0^+} x \cdot \ln(x) = 0$ as we have seen above.

$x \rightarrow 0^+$ $x \rightarrow 0^+$

We say that $f(x)$ grows faster than $g(x)$ if:

$$\lim_{x \rightarrow \infty} \frac{f(x)}{g(x)} = \infty \quad \text{or} \quad \lim_{x \rightarrow \infty} \frac{g(x)}{f(x)} = 0 \quad \text{and denote } f(x) \gg g(x).$$

L'Hôpital's rule: Assume that $f(x)$ and $g(x)$ are differentiable in an interval (b, ∞) .

Assume also that $g'(x) \neq 0$ for $x > b$. If $\lim_{x \rightarrow \infty} f(x)$ and

$\lim_{x \rightarrow \infty} g(x)$ exist and are either both infinite or zero, then:

$$\lim_{x \rightarrow \infty} \frac{f(x)}{g(x)} = \lim_{x \rightarrow \infty} \frac{f'(x)}{g'(x)}$$

whenever the limit exists. This also holds for $x \rightarrow -\infty$.

Example: Which of $f(x) = x^2$ and $g(x) = x \cdot \ln(x)$ grows faster?

$$\lim_{x \rightarrow \infty} \frac{f(x)}{g(x)} = \lim_{x \rightarrow \infty} \frac{x^2}{x \cdot \ln(x)} = \lim_{x \rightarrow \infty} \frac{x}{\ln(x)} = \lim_{x \rightarrow \infty} \frac{1}{\frac{1}{x}} = \lim_{x \rightarrow \infty} = \infty$$

LHR LHR

so $f(x)$ grows faster.

Example: Evaluate:

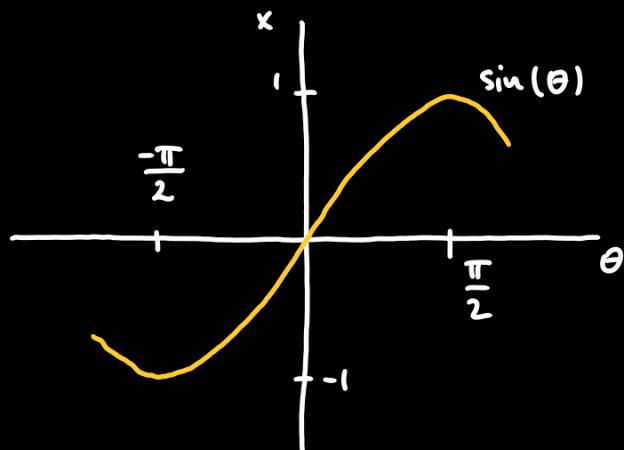
$$\begin{aligned} \lim_{x \rightarrow \infty} \frac{\sqrt{x}}{\ln(x)^2} &= \lim_{x \rightarrow \infty} \frac{\frac{1}{2\sqrt{x}}}{\frac{2}{x} \cdot \ln(x)} = \lim_{x \rightarrow \infty} \frac{\sqrt{x}}{4 \cdot \ln(x)} = \lim_{x \rightarrow \infty} \frac{\frac{1}{2\sqrt{x}}}{\frac{4}{x}} = \\ &= \lim_{x \rightarrow \infty} \frac{\sqrt{x}}{8} = \infty. \end{aligned}$$

Growth rule of thumb:

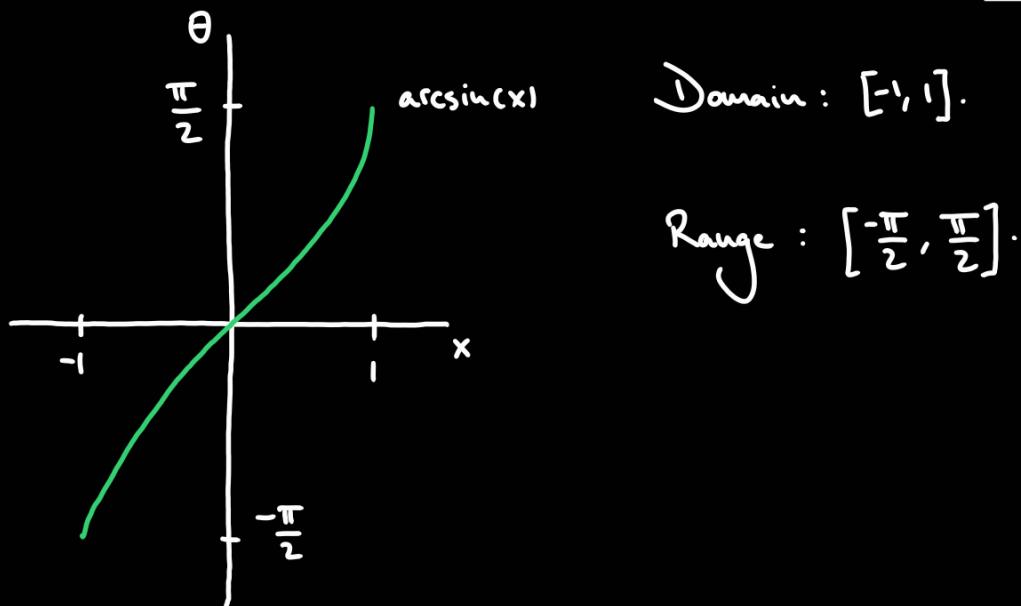
$e^x \gg x^n \gg \ln(x)$, n integer.

Section 7.8.: Inverse trigonometric functions.

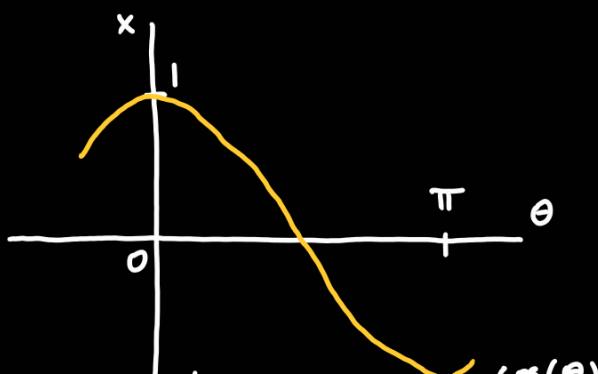
The function $f(\theta) = \sin(\theta)$ is one-to-one on $[-\frac{\pi}{2}, \frac{\pi}{2}]$.



Its inverse is called the arcsine function, denoted $\arcsin(x)$.

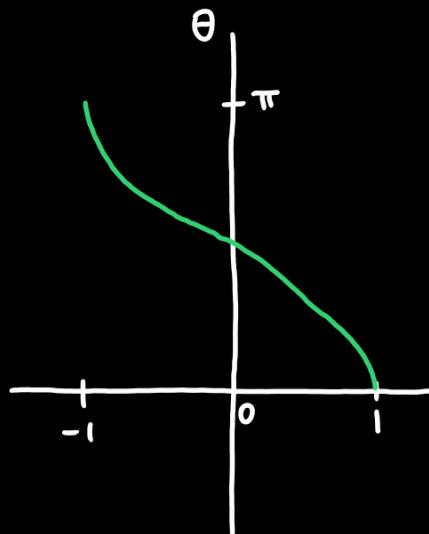


The function $(\theta) = \cos(\theta)$ is one-to-one on $[0, \pi]$.



f^{-1}

Its inverse is called the arccosine function, denoted $\arccos(x)$.



Domain: $[-1, 1]$.

Range: $[0, \pi]$.

Derivatives of arcsine and arccosine:

$$\frac{d}{dx}(\arcsin(x)) = \frac{1}{\sqrt{1-x^2}} , \quad \frac{d}{dx}(\arccos(x)) = \frac{-1}{\sqrt{1-x^2}}$$

Example: $\frac{d}{dx}(\arcsin(x^2)) = \frac{1}{\sqrt{1-x^4}} \cdot \frac{d}{dx}(x^2) = \frac{2x}{\sqrt{1-x^4}}$.

The function $f(\theta) = \tan(\theta)$ is one-to-one on $(-\frac{\pi}{2}, \frac{\pi}{2})$. Its inverse is

called the arctangent function, denoted $\arctan(x)$.

The function $f(\theta) = \cot(\theta)$ is one-to-one on $(0, \pi)$. Its inverse is called

the arccotangent function, denoted $\text{arccotan}(x)$.

The function $f(\theta) = \sec(\theta)$ is one-to-one on $[0, \frac{\pi}{2})$ and $(\frac{\pi}{2}, \pi]$. Its inverse

is called the arcsecant function, denoted $\text{arcsec}(x)$.

The function $f(\theta) = \csc(\theta)$ is one-to-one on $\left[-\frac{\pi}{2}, 0\right)$ and $\left(0, \frac{\pi}{2}\right]$. Its inverse

is called the arccosecant function, denoted $\text{arccsc}(x)$.

Derivatives of inverse trigonometric functions:

$$\begin{aligned}\frac{d}{dx}(\arctan(x)) &= \frac{1}{x^2+1}, & \frac{d}{dx}(\text{arccot}(x)) &= \frac{-1}{x^2+1}, \\ \frac{d}{dx}(\text{arcsec}(x)) &= \frac{1}{|x|\sqrt{x^2-1}}, & \frac{d}{dx}(\text{arccsc}(x)) &= \frac{-1}{|x|\sqrt{x^2-1}}.\end{aligned}$$

Example: Integrate:

$$\int_0^1 \frac{dx}{x^2+1} = \arctan(x) \Big|_0^1 = \arctan(1) - \arctan(0) = \frac{\pi}{4} - 0 = \frac{\pi}{4}.$$

Example: Integrate:

$$\int_{\frac{1}{\sqrt{2}}}^1 \frac{dx}{x\sqrt{4x^2-1}} = \int_{\sqrt{2}}^2 \frac{\frac{1}{2}du}{\frac{1}{2}u\sqrt{u^2-1}} = \int_{\sqrt{2}}^2 \frac{du}{u\sqrt{u^2-1}} = \text{arcsec}(u) \Big|_{\sqrt{2}}^2 =$$

$$\begin{aligned}u &= 2x & x &= 1 \rightarrow u = 2 \\ du &= 2dx & x = \frac{1}{\sqrt{2}} \rightarrow u = \sqrt{2}\end{aligned}$$

$$= \text{arcsec}(2) - \text{arcsec}(\sqrt{2}) = \frac{\pi}{3} - \frac{\pi}{4} = \frac{\pi}{12}.$$

Example: Integrate:

$$\int_{-\frac{3}{4}}^0 \frac{dx}{\sqrt{9-16x^2}} = \int_{-\frac{3}{4}}^0 \frac{dx}{3\sqrt{1-\left(\frac{4x}{3}\right)^2}} = \int_{-1}^0 \frac{\frac{3}{4}du}{3\sqrt{1-u^2}} = \frac{1}{4} \int_{-1}^0 \frac{du}{\sqrt{1-u^2}} =$$
$$\sqrt{9-16x^2} = \sqrt{9\left(1-\frac{16x^2}{9}\right)} = 3\sqrt{1-\left(\frac{4x}{3}\right)^2} \quad u = \frac{4x}{3} \quad u(0) = 0 \\ du = \frac{4}{3}dx \quad u\left(-\frac{3}{4}\right) = -1$$

$$= \frac{1}{4} \left[\arcsin(u) \right]_{-1}^0 = \frac{1}{4} (\arcsin(0) - \arcsin(-1)) = \frac{1}{4} \left(-\frac{\pi}{2} - (-\frac{\pi}{2}) \right) = \frac{\pi}{8}$$

$$= \frac{1}{4} \arcsin(x) \Big|_{-1}^1 = \frac{1}{4} (\arcsin(0) - \arcsin(-1)) = \frac{1}{4} (0 - (-\frac{\pi}{2})) = \frac{\pi}{8}$$

Section 7.9: Hyperbolic functions.

The hyperbolic functions are specific combinations of e^x and e^{-x} .

Hyperbolic sine:

$$\sinh(x) = \frac{e^x - e^{-x}}{2}$$

Hyperbolic cosine:

$$\cosh(x) = \frac{e^x + e^{-x}}{2}$$

Hyperbolic tangent:

$$\tanh(x) = \frac{\sinh(x)}{\cosh(x)} = \frac{e^x - e^{-x}}{e^x + e^{-x}}$$

Hyperbolic cotangent:

$$\coth(x) = \frac{\cosh(x)}{\sinh(x)} = \frac{e^x + e^{-x}}{e^x - e^{-x}}$$

Hyperbolic secant:

$$\operatorname{sech}(x) = \frac{1}{\cosh(x)} = \frac{2}{e^x + e^{-x}}$$

Hyperbolic cosecant:

$$\operatorname{csch}(x) = \frac{1}{\sinh(x)} = \frac{2}{e^x - e^{-x}}$$

Derivatives of hyperbolic functions:

$$\frac{d}{dx}(\sinh(x)) = \cosh(x),$$

$$\frac{d}{dx}(\cosh(x)) = \sinh(x)$$

$$\frac{d}{dx}(\tanh(x)) = \operatorname{sech}^2(x),$$

$$\frac{d}{dx}(\coth(x)) = -\operatorname{csch}^2(x)$$

$$\frac{d}{dx}(\operatorname{sech}(x)) = -\operatorname{sech}(x) \cdot \tanh(x),$$

$$\frac{d}{dx}(\operatorname{csch}(x)) = -\operatorname{csch}(x) \cdot \coth(x).$$

Example: Simplify:

$$\cosh^2(x) - \sinh^2(x) = \left(\frac{e^x + e^{-x}}{2}\right)^2 - \left(\frac{e^x - e^{-x}}{2}\right)^2 = \frac{e^{2x} + e^{-2x} + 2}{4} - \frac{e^{2x} - e^{-2x}}{4} = \frac{2}{4} = \frac{1}{2}$$

$$-\frac{e^{2x} + e^{-2x} - 2}{4} = \frac{2}{4} + \frac{2}{4} = 1.$$

Example: Differentiate:

$$\begin{aligned}\frac{d}{dx}(\coth(x)) &= \frac{d}{dx}\left(\frac{\cosh(x)}{\sinh(x)}\right) = \frac{\frac{d}{dx}(\cosh(x)) \cdot \sinh(x) - \cosh(x) \cdot \frac{d}{dx}(\sinh(x))}{\sinh^2(x)} = \\ &= \frac{\sinh^2(x) - \cosh^2(x)}{\sinh^2(x)} = \frac{-1}{\sinh^2(x)} = -\operatorname{csch}^2(x).\end{aligned}$$

Inverse hyperbolic functions and their derivatives:

<u>Function</u>	<u>Domain</u>	<u>Derivative</u>
$\operatorname{arcsinh}(x)$	\mathbb{R}	$\frac{1}{\sqrt{x^2+1}}$
$\operatorname{arccosh}(x)$	$[1, \infty)$	$\frac{1}{\sqrt{x^2-1}}$
$\operatorname{arctanh}(x)$	$(-1, 1)$	$\frac{1}{1-x^2}$
$\operatorname{arccoth}(x)$	$(-\infty, -1) \cup (1, \infty)$	$\frac{1}{1-x^2}$
$\operatorname{arcsech}(x)$	$(0, 1]$	$\frac{-1}{x\sqrt{1-x^2}}$
$\operatorname{arccsch}(x)$	$(-\infty, 0) \cup (0, \infty)$	$\frac{-1}{ x \sqrt{x^2+1}}$

Example: Differentiate:

$$\frac{d}{dx}(\operatorname{arctanh}(x)) = \frac{1}{\operatorname{sech}^2(\operatorname{arctanh}(x))} = \frac{1}{1-x^2}.$$

if $g(x)$ is the inverse of $f(x)$,

$$1 = \cosh^2(t) - \sinh^2(t)$$

$$\text{then } g'(x) = \frac{1}{f'(g(x))}.$$

$$f(x) = \tanh(x), \quad f'(x) = \operatorname{sech}^2(x)$$

$$g(x) = \operatorname{arctanh}(x)$$

$$\frac{1}{\cosh^2(t)} = 1 - \frac{\sinh^2(t)}{\cosh^2(t)}$$

$$\operatorname{sech}^2(t) = 1 - \operatorname{tanh}^2(t)$$

$\left\{ \begin{array}{l} t = \operatorname{arctanh}(x) \\ \operatorname{sech}^2(\operatorname{arctanh}(x)) = 1 - x^2 \end{array} \right.$

Section 8.1: Integration by parts.

The formula for integration by parts is given by the product rule for differentiation:

$$\frac{d}{dx}(u(x) \cdot v(x)) = \frac{d}{dx}(u(x)) \cdot v(x) + u(x) \cdot \frac{d}{dx}(v(x)), \text{ so:}$$

Integration by parts:

$$\boxed{\int u(x)v'(x)dx = u(x)v(x) - \int v(x)u'(x)dx}$$

Or in shorthand: $\int u \cdot dv = u \cdot v - \int v \cdot du$. Guidelines for choosing u and v :

1. We want $\frac{du}{dx}$ simpler than u .

2. We need to know how to evaluate $\int v'(x)dx$ to compute v .

Example: Evaluate:

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

\uparrow
 $u = x$
 $\frac{du}{dx} = 1$
 $\frac{dv}{dx} = \cos(x)$
 $v = \sin(x)$

Example: Evaluate:

$$\int x \cdot e^x dx = x e^x - \int e^x dx = x e^x - e^x + C$$

\uparrow
 $u = x$
 $\frac{du}{dx} = 1$
 $\frac{dv}{dx} = e^x$
 $v = e^x$

$$\frac{du}{dx} = e^x \quad v = e^x$$

However, if we swap our choices:

$$\int x \cdot e^x dx = \frac{x^2}{2} \cdot e^x - \int \frac{x^2}{2} \cdot e^x dx, \text{ which is a harder integral than the original.}$$



$$u = e^x \quad \frac{du}{dx} = e^x$$

$$\frac{dv}{dx} = x \quad v = \frac{x^2}{2}$$

Example: Evaluate:

$$\begin{aligned} \int x^2 \cdot \cos(x) dx &= x^2 \cdot \sin(x) - \int 2x \cdot \sin(x) dx = x^2 \cdot \sin(x) - 2 \int x \cdot \sin(x) dx = \\ &\quad \uparrow \qquad \qquad \qquad \uparrow \\ &\quad u = x^2 \quad \frac{du}{dx} = 2x \\ &\quad \frac{dv}{dx} = \cos(x) \quad v = \sin(x) \\ &= x^2 \cdot \sin(x) - 2 \cdot \left(-x \cdot \cos(x) - \int 1 \cdot (-\cos(x)) dx \right) = \\ &= x^2 \cdot \sin(x) + 2x \cdot \cos(x) - 2 \int \cos(x) dx = x^2 \cdot \sin(x) + 2x \cdot \cos(x) - 2 \sin(x) + C_1. \end{aligned}$$

Example: Evaluate:

$$\begin{aligned} \int e^x \cdot \cos(x) dx &= e^x \cdot \cos(x) - \int e^x \cdot (-\sin(x)) dx = e^x \cdot \cos(x) + \int e^x \cdot \sin(x) dx = \\ &\quad \uparrow \qquad \qquad \qquad \uparrow \\ &\quad u = \cos(x) \quad \frac{du}{dx} = -\sin(x) \\ &\quad \frac{dv}{dx} = e^x \quad v = e^x \\ &= e^x \cdot \cos(x) + \left(e^x \cdot \sin(x) - \int e^x \cdot \cos(x) dx \right) = e^x \cdot (\cos(x) + \sin(x)) - \int e^x \cdot \cos(x) dx \end{aligned}$$

$\int_0:$

$$2 \cdot \int e^x \cdot \cos(x) dx = e^x \cdot (\cos(x) + \sin(x))$$

$$\int_0^\pi e^x \cdot (\cos(x) + \sin(x)) dx$$

$$\int e^x \cdot \cos(x) dx = \frac{e^x}{2} (\cos(x) + \sin(x)) + C.$$

Integration by parts for definite integrals:

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

Example: Evaluate:

$$\int_1^3 \ln(x) dx = x \ln(x) \Big|_1^3 - \int_1^3 x \cdot \frac{1}{x} dx = x \ln(x) \Big|_1^3 - \int_1^3 dx = x \ln(x) \Big|_1^3 - x \Big|_1^3 =$$

$$\begin{aligned} u &= \ln(x) & \frac{du}{dx} &= \frac{1}{x} \\ \frac{dv}{dx} &= 1 & v &= x \end{aligned}$$

$$= (3 \ln(3) - 0) - (3 - 1) = 3 \ln(3) - 2.$$

Example: Evaluate:

$$\int x^u e^x dx = x^u e^x - \int u x^{u-1} e^x dx = x^u e^x - u \int x^{u-1} e^x dx.$$

$$\begin{aligned} u &= x^u & \frac{du}{dx} &= u x^{u-1} \\ \frac{dv}{dx} &= e^x & v &= e^x \end{aligned}$$

Example: Evaluate:

$$\int x^3 e^x dx = x^3 e^x - 3 \int x^2 e^x dx = x^3 e^x - 3 \left(x^2 e^x - 2 \int x e^x dx \right) = x^3 e^x - 3 x^2 e^x + 6 \int x e^x dx =$$

$$= x^3 e^x - 3 x^2 e^x + 6 \left(x e^x - \int e^x dx \right) = x^3 e^x - 3 x^2 e^x + 6 x e^x - 6 e^x + C =$$

$$= (x^3 - 3x^2 + 6x - 6) e^x + C.$$

Section 8.5: The method of partial fractions

When integrating a function $f(x) = \frac{P(x)}{Q(x)}$, we should try to rewrite $f(x)$ as a sum of simpler fractions that can be integrated directly.

Sum of simpler fractions that can be integrated directly.

Example: Evaluate:

$$\int \frac{dx}{x^2-1} = \int \frac{dx}{(x-1)(x+1)} = \frac{1}{2} \int \frac{dx}{x-1} - \frac{1}{2} \int \frac{dx}{x+1} = \frac{\ln|x-1|}{2} - \frac{\ln|x+1|}{2}$$
$$\frac{1}{(x-1)(x+1)} = \frac{1}{2} \left(\frac{1}{x-1} - \frac{1}{x+1} \right)$$

If the degree of $P(x)$ is less than the degree of $Q(x)$ and $Q(x)$ factors as a

product of distinct linear factors: $Q(x) = (x-a_1) \cdots (x-a_n)$, then there is a

partial fraction decomposition: $\frac{P(x)}{Q(x)} = \frac{A_1}{x-a_1} + \cdots + \frac{A_n}{x-a_n}$.

Each distinct factor $x-a$ in the denominator contributes a term $\frac{A}{x-a}$ to the

partial fraction decomposition.

Example: Decompose into partial fractions:

$$\frac{5x^2+x-28}{x^3-4x^2+x+6} = \frac{5x^2+x-28}{(x+1)(x-2)(x-3)} = \frac{-2}{x+1} + \frac{2}{x-2} + \frac{5}{x-3}$$

Example: Decompose into partial fractions and integrate $\frac{x^2+2}{2x^3-6x^2-12x+16}$.

We first factor the denominator: $2x^3-6x^2-12x+16 = (x-1)(2x-8)(x+2)$.

Then we write the decomposition: $\frac{x^2+2}{2x^3-6x^2-12x+16} = \frac{A}{x-1} + \frac{B}{2x-8} + \frac{C}{x+2}$.

Multiply by $(x-1)(2x-8)(x+2)$ to clear denominators:

$$x^2 + 2 = A \cdot (2x - 8)(x+2) + B \cdot (x-1)(x+2) + C \cdot (x-1)(2x-8).$$

To compute A , set $x=1$: $1^2 + 2 = A \cdot (2-8)(1+2)$ so $A = \frac{-1}{6}$.

To compute B , set $x=4$: $4^2 + 2 = B \cdot (4-1)(4+2)$ so $B = 1$.

To compute C , set $x=-2$: $(-2)^2 + 2 = C \cdot (-2-1)(-4-8)$ so $C = \frac{1}{6}$.

$$\text{Then: } \frac{x^2 + 2}{2x^3 - 6x^2 - 12x + 16} = \frac{\frac{-1}{6}}{x-1} + \frac{1}{2x-8} + \frac{\frac{1}{6}}{x+2}.$$

We can then integrate:

$$\begin{aligned} \int \frac{x^2 + 2}{2x^3 - 6x^2 - 12x + 16} dx &= \frac{-1}{6} \int \frac{dx}{x-1} + \int \frac{dx}{2x-8} + \frac{1}{6} \int \frac{dx}{x+2} = \\ &= \frac{-1}{6} \ln|x-1| + \frac{1}{2} \ln|x-4| + \frac{1}{6} \ln|x+2| + C. \end{aligned}$$

Remark: We can also factor: $2x^3 - 6x^2 - 12x + 16 = 2(x-1)(x-4)(x+2)$ and use

the decomposition:

$$\frac{x^2 + 2}{2x^3 - 6x^2 - 12x + 16} = \frac{x^2 + 2}{2(x-1)(x-4)(x+2)} = \frac{D}{x-1} + \frac{E}{x-4} + \frac{F}{x+2}$$

to obtain the same final integral.

If the degree of $P(x)$ is less than the degree of $Q(x)$ and $Q(x)$ factors as a

product of repeated linear factors: $Q(x) = (x-a_1)^{M_1} \cdots (x-a_n)^{M_n}$, then there is a

partial fraction decomposition:

$$\frac{P(x)}{Q(x)} = \frac{A_{11}}{x-a_1} + \frac{A_{12}}{(x-a_1)^2} + \cdots + \frac{A_{1M_1}}{(x-a_1)^{M_1}} + \cdots + \frac{A_{n1}}{x-a_n} + \frac{A_{n2}}{(x-a_n)^2} + \cdots + \frac{A_{nM_n}}{(x-a_n)^{M_n}}$$

Example: Decompose into partial fractions and integrate $\frac{3x-9}{x^3+3x^2-4}$.

We first factor the denominator: $x^3+3x^2-4 = (x-1)(x+2)^2$.

Then we write the decomposition: $\frac{3x-9}{x^3+3x^2-4} = \frac{A}{x-1} + \frac{B_1}{x+2} + \frac{B_2}{(x+2)^2}$.

Multiply by $(x-1)(x+2)^2$ to clear denominators:

$$3x-9 = A(x+2)^2 + B_1(x-1)(x+2) + B_2(x-1).$$

To compute A , set $x=1$: $3 \cdot 1 - 9 = A(1+2)^2$ so $A = \frac{-2}{3}$.

To compute B_2 , set $x=-2$: $3 \cdot (-2) - 9 = B_2(-2-1)$ so $B_2 = 5$.

To compute B_1 , set $x=2$: $3 \cdot 2 - 9 = \frac{-2}{3} \cdot (2+2)^2 + B_1(2-1)(2+2) + 5(2-1)$ so $B_1 = \frac{2}{3}$.

$$\text{Then: } \frac{3x-9}{x^3+3x^2-4} = \frac{\frac{-2}{3}}{x-1} + \frac{\frac{2}{3}}{x+2} + \frac{5}{(x+2)^2}.$$

We can then integrate:

$$\int \frac{3x-9}{x^3+3x^2-4} dx = \frac{-2}{3} \int \frac{dx}{x-1} + \frac{2}{3} \int \frac{dx}{x+2} + 5 \int \frac{dx}{(x+2)^2} =$$

$$= \frac{-2}{3} \ln|x-1| + \frac{2}{3} \ln|x+2| + \frac{-5}{x+2} + C.$$

A power $(ax^2+bx+c)^M$ of a quadratic polynomial ax^2+bx+c that cannot be written

as a product of two linear factors contributes to a partial fraction decomposition with:

$$\frac{A_1x+B_1}{x^2+1} + \frac{A_2x+B_2}{(x-1)^2} + \dots + \frac{A_Mx+B_M}{(x-1)^M}$$

$$ax^2 + bx + c = (ax^2 + bx + c)^{1/2}$$

Example: Decompose into partial fractions:

$$\frac{4-x}{x(x^2+4x+2)} = \frac{1}{x} + \frac{-(x+4)}{x^2+4x+2} + \frac{-(2x+9)}{(x^2+4x+2)^2}$$

Example: Decompose into partial fractions and integrate $\frac{4-x}{x^5+4x^3+4x}$.

We first factor the denominator: $x^5+4x^3+4x = x(x^2+2)^2$.

Then we write the decomposition: $\frac{4-x}{x^5+4x^3+4x} = \frac{A}{x} + \frac{Bx+C}{x^2+2} + \frac{Dx+E}{(x^2+2)^2}$.

Find the coefficients: $A=1, B=-1, C=0, D=-2, E=-1$.

We can then integrate:

$$\int \frac{4-x}{x^5+4x^3+4x} dx = \int \frac{dx}{x} - \int \frac{x dx}{x^2+2} - \int \frac{2x+1}{(x^2+2)^2} dx$$

As:

$$\int \frac{dx}{x} = \ln|x| + C$$

$$\int \frac{x dx}{x^2+2} = \dots = \frac{1}{2} \ln|x^2+2| + C$$

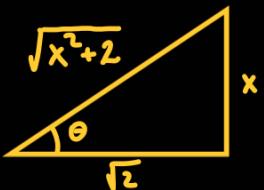
$$\begin{aligned} u &= x^2+2 \\ du &= 2x dx \end{aligned}$$

$$\int \frac{2x+1}{(x^2+2)^2} dx = \int \frac{2x dx}{(x^2+2)^2} + \int \frac{dx}{(x^2+2)^2}$$

$$\int \frac{2x dx}{(x^2+2)^2} = \dots = \frac{-1}{x^2+2} + C$$

$$\begin{aligned} u &= x^2+2 \\ du &= 2x dx \end{aligned}$$

$$\int \frac{dx}{(x^2+2)^2} = \int \frac{\sqrt{2} \cdot \sec^2(\theta) d\theta}{(2 \cdot \tan^2(\theta) + 2)^2} = \int \frac{\sqrt{2} \cdot \sec^2(\theta) d\theta}{4 \cdot \sec^4(\theta)} = \frac{\sqrt{2}}{4} \int \cos^2(\theta) d\theta =$$



$$x = \sqrt{2} \cdot \tan(\theta) \quad dx = \sqrt{2} \cdot \sec^2(\theta) d\theta$$

$$x^2 + 2 = 2 \cdot \tan^2(\theta) + 2 = 2 \cdot \sec^2(\theta)$$

$$\tan^2(\theta) + 1 = \sec^2(\theta)$$

$$= \frac{\sqrt{2}}{4} \left(\frac{\theta}{2} + \frac{\sin(\theta) \cdot \cos(\theta)}{2} \right) + C_1 =$$

integration by parts

$$= \frac{\sqrt{2}}{8} \cdot \arctan\left(\frac{x}{\sqrt{2}}\right) + \frac{\sqrt{2}}{8} \cdot \frac{x}{\sqrt{x^2+2}} \cdot \frac{\sqrt{2}}{\sqrt{x^2+2}} + C_1 =$$

$$= \frac{1}{4\sqrt{2}} \cdot \arctan\left(\frac{x}{\sqrt{2}}\right) + \frac{x}{4(x^2+2)} + C_1$$

We finally have:

$$\int \frac{4-x}{x^5+4x^3+4x} dx = \ln|x| - \frac{1}{2} \ln|x^2+2| + \frac{\frac{x}{4}-1}{x^2+2} - \frac{1}{4\sqrt{2}} \cdot \arctan\left(\frac{x}{\sqrt{2}}\right).$$

If the degree of $P(x)$ is greater than or equal to the degree of $Q(x)$, do the long division of polynomials.

Section 9.1.: Arc length and surface area.

The length of a curve is called arc length.

Formula for arc length:

Assume that $f'(x)$ exists and is continuous on $[a, b]$.

Then the arc length of $f(x)$ over $[a, b]$ is:

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

Example: Find the arc length of $f(x) = \frac{x^3}{12} + x^{-1}$ over $[1, 3]$.

Compute first:

$$1 + (f'(x))^2 = 1 + \left(\frac{1}{4}x^2 - x^{-2}\right)^2 = 1 + \frac{x^4}{16} - \frac{1}{2}x^{-4} = \frac{x^4}{16} + \frac{1}{2}x^{-4} = \left(\frac{x^2}{4} + x^{-2}\right)^2.$$

Compute the arc length:

$$s = \int_1^3 \sqrt{1 + (f'(x))^2} dx = \int_1^3 \left(\frac{x^2}{4} + x^{-2}\right) dx = \left. \frac{x^3}{12} - x^{-1} \right|_1^3 = \left(\frac{9}{4} - \frac{1}{3}\right) - \left(\frac{1}{12} - 1\right) = \frac{17}{6}.$$

Example: Find the arc length of $f(x) = \cosh(x)$ over $[0, 2]$.

Compute first:

$$1 + (f'(x))^2 = 1 + (\sinh(x))^2 = \cosh^2(x)$$

\uparrow \uparrow
 $\frac{d}{dx}(\cosh(x)) = \sinh(x)$ $\cosh^2(x) + \sinh^2(x) = 1$

Since $\cosh^2(x) \geq 0$ for $x \geq 0$ we have $\sqrt{\cosh^2(x)} = \cosh(x)$, we compute the arc length:

$$s = \int_0^a \sqrt{1 + (f'(x))^2} dx = \int_0^a \sqrt{\cosh^2(x)} dx = \int_0^a \cosh(x) dx = \sinh(x) \Big|_0^a = \sinh(a).$$

Formula for the area of a surface of revolution:

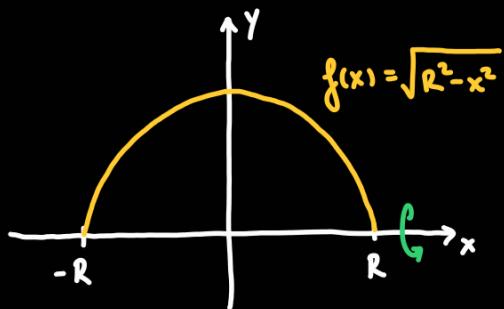
Assume that $f(x) \geq 0$ and that $f'(x)$ exists and is continuous on $[a, b]$. The surface

area S of the surface obtained by rotating the graph of $f(x)$ about the x -axis for

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

Example: Calculate the surface area of a sphere of radius R.

A semicircle of radius R is given by the function $f(x) = \sqrt{R^2 - x^2}$. We obtain a sphere by rotating about the x-axis.



Compute first:

$$f'(x) = \frac{-x}{\sqrt{R^2 - x^2}}, \quad 1 + (f'(x))^2 = 1 + \frac{x^2}{R^2 - x^2} = \frac{R^2}{R^2 - x^2}.$$

Compute the surface area:

$$\begin{aligned} S &= 2\pi \int_{-R}^R f(x) \sqrt{1 + (f'(x))^2} dx = 2\pi \int_{-R}^R \sqrt{R^2 - x^2} \cdot \frac{R}{\sqrt{R^2 - x^2}} dx = 2\pi R \int_{-R}^R dx = \\ &= 2\pi (R - (-R)) = 4\pi R^2. \end{aligned}$$

Example: Find the surface area of the surface obtained by rotating the graph of

$$f(x) = \sqrt[3]{x} - \frac{\sqrt[3]{x^2}}{3}$$
 about the x-axis for $1 \leq x \leq 3$.

Compute first:

$$\begin{aligned} f'(x) &= \frac{1}{2\sqrt[3]{x}} - \frac{\sqrt[3]{x^2}}{2}, \quad 1 + (f'(x))^2 = 1 + \left(\frac{1}{2\sqrt[3]{x}} - \frac{\sqrt[3]{x^2}}{2}\right)^2 = 1 + \frac{x^{-1} - 2 + x}{4} = \\ &= x^{-1} + 2 + x \cdot \left(x^{\frac{1}{2}} + x^{-\frac{1}{2}}\right)^2 \end{aligned}$$

Compute the surface area:

$$S = 2\pi \int_1^3 f(x) \sqrt{1 + (f'(x))^2} dx = 2\pi \int_1^3 \left(x^{\frac{1}{2}} - \frac{x^{\frac{3}{2}}}{3} \right) \left(\frac{x^{\frac{1}{2}} + x^{-\frac{1}{2}}}{2} \right)^2 dx =$$
$$= \pi \int_1^3 \left(1 + \frac{2x}{3} - \frac{x^2}{3} \right) dx = \pi \left(x + \frac{x^2}{3} - \frac{x^3}{9} \right) \Big|_1^3 = \frac{16\pi}{9}.$$

Section 9.4.: Taylor polynomials.

For this section we assume that $f(x)$ is defined on some open interval and that all

higher derivatives $f^{(k)}(x)$ exist. Let I be an interval and x, a points in I .

Taylor polynomial centered at $x=a$:

$$T_n(x) = f(a) + \frac{f'(a)}{1!}(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \dots + \frac{f^{(n)}(a)}{n!}(x-a)^n = \sum_{j=0}^n \frac{f^{(j)}(a)}{j!}(x-a)^j$$

When $a=0$, we also call this the MacLaurin polynomial.

Example: Compute the third and fourth MacLaurin polynomials for $f(x)=e^x$.

Since $f^{(k)}(x)=e^x$ for all positive integer k , we have at $x=0$:

$$f(0) = f'(0) = f''(0) = f'''(0) = f^{(4)}(0) = 1.$$

The third MacLaurin polynomial is:

$$T_3(x) = f(0) + f'(0)(x-0) + \frac{f''(0)}{2}(x-0)^2 + \frac{f'''(0)}{6}(x-0)^3 = 1 + x + \frac{x^2}{2} + \frac{x^3}{6}.$$

We obtain $T_4(x)$ by adding the term of degree four to $T_3(x)$:

$$T_4(x) = T_3(x) + \frac{f^{(4)}(0)}{24} (x-0)^4 = 1 + x + \frac{x^2}{2} + \frac{x^3}{6} + \frac{x^4}{24}.$$

Example: Find the Taylor polynomials of $f(x) = \ln(x)$ centered at $a=1$.

Compute the derivatives:

$$f(x) = \ln(x), \quad f'(x) = x^{-1}, \quad f''(x) = -x^{-2}, \quad f'''(x) = 2x^{-3}, \quad f^{(4)}(x) = -3 \cdot 2 \cdot x^{-4},$$

so the pattern is $f^{(k)}(x) = \underbrace{(-1)^k}_{\text{alternating sign}} \underbrace{(k-1)!}_{\text{coefficients from the exponent rule}} x^{-k}$ for $k \geq 1$. Then:

$$\frac{f^{(k)}(1)}{k!} (x-1)^k = \frac{(-1)^k \cdot (k-1)! \cdot 1^k}{k!} (x-1)^k = \frac{(-1)^{k-1}}{k!} (x-1)^k \text{ so:}$$

$$T_n(x) = (x-1) - \frac{(x-1)^2}{2} + \frac{(x-1)^3}{3} - \dots + \frac{(-1)^n \cdot (x-1)^n}{n} = \sum_{j=1}^n \frac{(-1)^{j-1}}{j} (x-1)^j.$$

Useful MacLaurin and Taylor polynomials:

$f(x)$	a	polynomial
e^x	0	$T_n(x) = \sum_{j=0}^n \frac{x^j}{j!}$
$\sin(x)$	0	$T_{2n+1}(x) = T_{2n+2}(x) = \sum_{j=0}^n (-1)^j \frac{x^{2n+1}}{(2n+1)!}$
$\cos(x)$	0	$T_{2n}(x) = T_{2n+1}(x) = \sum_{j=0}^n (-1)^j \frac{x^{2n}}{(2n)!}$
$\ln(x)$	1	$T_n(x) = \sum_{j=1}^n \frac{(-1)^{n-j}}{n} \cdot (x-1)^n$
$\frac{1}{1-x}$	0	$T_n(x) = \sum_{j=0}^n x^j$

Error bound: Assume that $f^{(n+1)}(x)$ exists and is continuous, let K be a number such that $|f^{(n+1)}(u)| \leq K$ for all u between a and x , and let $T_n(x)$ be the n -th

Taylor polynomial centered at $x=a$. Then:

$$|f(x) - T_n(x)| \leq K \cdot \frac{|x-a|^{n+1}}{(n+1)!}$$

Namely, the error of approximating $f(x)$ by $T_n(x)$ is proportional to $\frac{|x-a|^{n+1}}{(n+1)!}$.

Example: Let $f(x) = \ln(x)$ and $a=1$. Bound the error of $T_3(x)$ at $x=1.2$.

Step 1: Find a value of K . We want $|f^{(4)}(u)| \leq K$ for all u between $a=1$ and

$x=1.2$. Since $f^{(4)}(x) = -6x^{-4}$, and $|f^{(4)}(x)| = 6x^{-4}$ is decreasing for $x > 0$,

its maximum value on $[1, 1.2]$ is $|f^{(4)}(1)| = 6$. Take $K=6$.

Step 2: Apply the error bound.

$$|\ln(1.2) - T_3(1.2)| \leq 6 \cdot \frac{|1.2-1|^4}{4!} = \frac{0.2^4}{4} = \frac{\left(\frac{2}{10}\right)^4}{4} = \frac{16}{40000} = \frac{1}{2500} = 0.0004.$$

Example: Let $f(x) = \cos(x)$ and $a=0.2$. Find an integer n such that the n -th

MacLaurin polynomial $T_n(x)$ has an error of less than 10^{-5} .

Step 1: Find a value of K . Since $|f^{(n)}(x)| = |\cos(x)|$ for n even, and $|f^{(n)}(x)|$ is

$|\sin(x)|$ for n odd, we always have $|f^{(n)}(x)| \leq 1$. Take $K=1$.

Step 2: Use the error bound to find a value of n .

$$|\cos(0.2) - \ln(0.2)| \leq 1 \cdot \frac{10.2 - 0}{(n+1)!} = \frac{0.2}{(n+1)!} < 10^{-5} = \frac{1}{100000}$$

↑
we must choose n so that this happens.

This is not solvable, so we find n by checking several values:

n	2	3	4
$\frac{0.2}{(n+1)!}$	$\frac{1}{750} \approx 0.0013$	$\frac{1}{15000} \approx 0.00007$	$\frac{1}{375000} \approx 0.0000027$

We have that the error is less than 10^{-5} for $n=4$.

Section 8.6.: Improper integrals

Improper integrals represent areas of unbounded regions. For a region to be unbounded, the interval of integration may be infinite or the function that is being integrated may tend to infinity.

Improper integral: The improper integral of $f(x)$ over $[a, \infty)$ is, if it exists :

$$\int_a^{\infty} f(x) dx = \lim_{R \rightarrow \infty} \int_a^R f(x) dx.$$

We say that the integral converges if the limit exists, and that it diverges if the

limit does not exist. The improper integral of $f(x)$ over $(-\infty, a]$ is, if it exists :

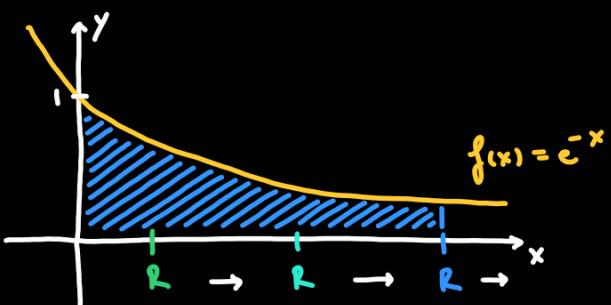
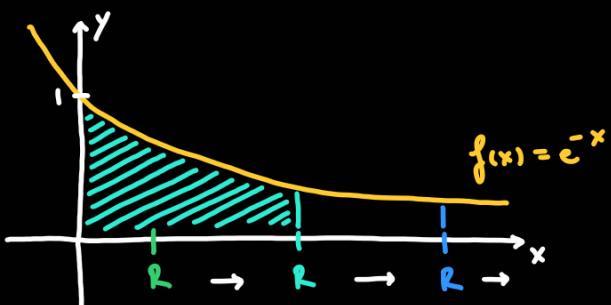
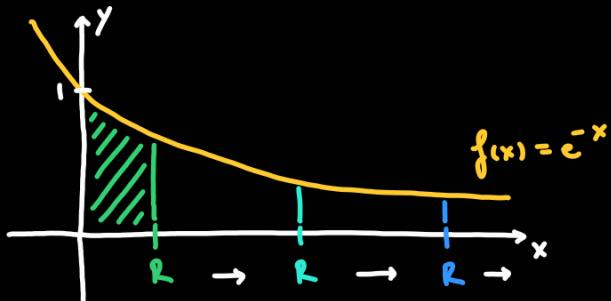
$$\int_{-\infty}^a f(x) dx = \lim_{R \rightarrow -\infty} \int_R^a f(x) dx.$$

An integral over $(-\infty, \infty)$ is computed by separating the infinities:

$$\int_{-\infty}^{\infty} f(x) dx = \int_{-\infty}^a f(x) dx + \int_a^{\infty} f(x) dx$$

Example: Evaluate:

$$\int_0^\infty e^{-x} dx = \lim_{R \rightarrow \infty} \int_0^R e^{-x} dx = \lim_{R \rightarrow \infty} (-e^{-x}) \Big|_0^R = \lim_{R \rightarrow \infty} (1 - e^{-R}) = 1.$$



Example: Evaluate:

$$\int_2^\infty \frac{dx}{x^3} = \lim_{R \rightarrow \infty} \int_2^R \frac{dx}{x^3} = \lim_{R \rightarrow \infty} \left(\frac{-x^{-2}}{2} \right) \Big|_2^R = \lim_{R \rightarrow \infty} \left(\frac{1}{8} - \frac{1}{2R^2} \right) = \frac{1}{8}.$$

Example: Determine whether $\int_{-\infty}^{-1} \frac{dx}{x}$ converges.

$$\int_{-\infty}^{-1} \frac{dx}{x} = \lim_{R \rightarrow -\infty} \int_R^{-1} \frac{dx}{x} = \lim_{R \rightarrow -\infty} \left[\ln|x| \right]_R^{-1} = \lim_{R \rightarrow -\infty} (\ln(1) - \ln|R|) = -\infty$$

The improper integral diverges.

The p-integral over $[a, \infty)$:

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

Example: Evaluate :

$$\begin{aligned} \int_0^{\infty} x e^{-x} dx &= \lim_{R \rightarrow \infty} \int_0^R x e^{-x} dx = \lim_{R \rightarrow \infty} \underset{\uparrow R \rightarrow \infty}{-(x+1)e^{-x}} \Big|_0^R = \lim_{R \rightarrow \infty} \left(-(R+1)e^{-R} + 1 \right) = \lim_{R \rightarrow \infty} \left(1 - \frac{R+1}{e^R} \right) = \\ \int x e^{-x} dx &= -x e^{-x} + \int e^{-x} dx = -x e^{-x} - e^{-x} = -(x+1)e^{-x} + C. \\ u = x & \quad du = 1 \\ dv = e^{-x} & \quad v = -e^{-x} \\ &= 1 - \lim_{R \rightarrow \infty} \frac{R+1}{e^R} = 1 - \lim_{R \rightarrow \infty} \frac{1}{e^R} = 1. \\ &\text{L'Hôpital's Rule} \end{aligned}$$

Integrands with infinite discontinuities:

If $f(x)$ is continuous on $[a, b)$ but discontinuous at $x=b$, then :

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

If $f(x)$ is continuous on $(a, b]$ but discontinuous at $x=a$, then :

$$\int_a^b f(x) dx = \lim_{R \rightarrow a^+} \int_R^b f(x) dx.$$

We say that the integral converges if the limit exists, and that it diverges if the limit does not exist.

Example: Evaluate :

$$\int_0^9 \frac{dx}{\sqrt[3]{x}} = \lim_{R \rightarrow 0^+} \int_0^R x^{-\frac{1}{3}} dx = \lim_{R \rightarrow 0^+} 2x^{1/2} \Big|_R^9 = \lim_{R \rightarrow 0^+} (6 - 2\sqrt{R}) = 6.$$

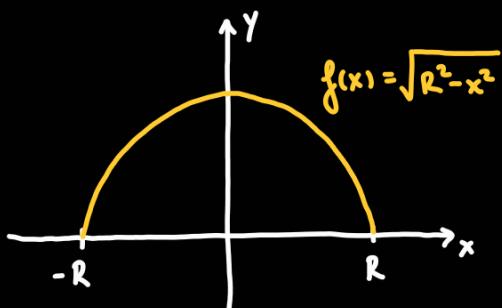
$$\int_0^{\frac{1}{2}} \frac{dx}{x} = \lim_{R \rightarrow 0^+} \int_R^{\frac{1}{2}} \frac{dx}{x} = \lim_{R \rightarrow 0^+} \ln|x| \Big|_R^{\frac{1}{2}} = \lim_{R \rightarrow 0^+} \left(\ln\left(\frac{1}{2}\right) - \ln(R) \right) = +\infty.$$

The p-integral over $[0, a]$:

$$\int_0^a \frac{dx}{x^p} = \begin{cases} \frac{a^{1-p}}{1-p} & \text{if } p < 1, \\ \text{diverges} & \text{if } p \geq 1. \end{cases}$$

Example: Calculate the length of one quarter of the unit circle.

A semicircle of radius R is given by the function $f(x) = \sqrt{R^2 - x^2}$. We obtain a unit circle by setting $R=1$. One quarter is given by the interval $[0, 1]$.



Compute first:

$$f'(x) = \frac{-x}{\sqrt{1-x^2}}, \quad 1 + (f'(x))^2 = 1 + \frac{x^2}{1-x^2} = \frac{1}{1-x^2}.$$

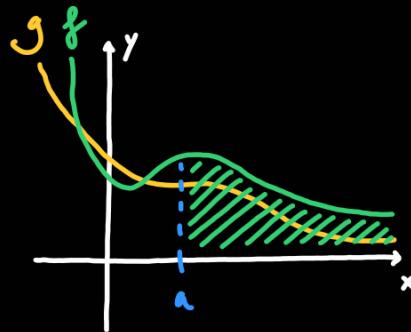
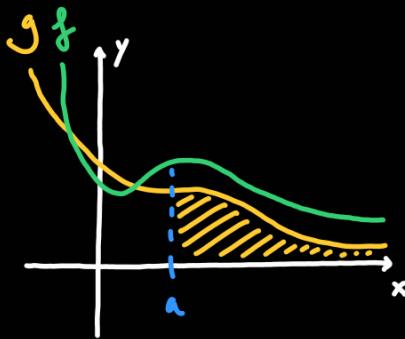
Compute the arc length:

$$\begin{aligned} s &= \int_0^1 \sqrt{1 + (f'(x))^2} dx = \int_0^1 \frac{dx}{\sqrt{1-x^2}} = \lim_{R \rightarrow 1^-} \int_0^R \frac{dx}{\sqrt{1-x^2}} = \lim_{R \rightarrow 1^-} \arcsin(x) \Big|_0^R = \\ &= \lim_{R \rightarrow 1^-} (\arcsin(R) - \arcsin(0)) = \arcsin(1) - \arcsin(0) = \frac{\pi}{2}. \end{aligned}$$

Comparison test for improper integrals: Assume that $f(x) \geq g(x) \geq 0$ for $x \geq a$.

If $\int_a^\infty f(x)dx$ converges, then $\int_a^\infty g(x)dx$ converges.

If $\int_a^\infty g(x)dx$ diverges, then $\int_a^\infty f(x)dx$ diverges.



Example: Show that $\int_1^\infty \frac{e^{-x}}{x} dx$ converges.

For $x \geq 1$ we have $0 \leq \frac{e^{-x}}{x} \leq e^{-x}$, so $0 \leq \int_1^\infty \frac{e^{-x}}{x} dx \leq \int_1^\infty e^{-x} dx = \frac{1}{e}$.

$$\int_1^\infty e^{-x} dx = \lim_{R \rightarrow \infty} \int_1^R e^{-x} dx = \lim_{R \rightarrow \infty} -e^{-x} \Big|_0^R = \frac{1}{e}$$

Example: Show that $\int_1^\infty \frac{dx}{\sqrt{x+e^{3x}}}$ converges.

For $x \geq 1$ we have $\sqrt{x+e^{3x}} \geq e^{3x}$ so $\frac{1}{\sqrt{x+e^{3x}}} \leq \frac{1}{e^{3x}}$. Moreover:

$$\int_1^\infty e^{-3x} dx = \lim_{R \rightarrow \infty} \int_1^R e^{-3x} dx = \lim_{R \rightarrow \infty} \frac{-e^{-3x}}{3} \Big|_0^R = \frac{1}{3} \text{ converges.}$$

By the Comparison Test, $\int_1^\infty \frac{dx}{\sqrt{x+e^{3x}}}$ converges.

However, we also have $\sqrt{x+e^{3x}} \geq \sqrt{x}$ so $\frac{1}{\sqrt{x+e^{3x}}} \leq \frac{1}{\sqrt{x}}$ for $x \geq 1$. This does not

help because $\int_1^\infty \frac{dx}{\sqrt{x}}$ diverges, so it says nothing about our smaller integral.

Section 11.1.: Sequences

A sequence is an ordered collection of numbers defined by a function $f(n)$, n integer.

The values $a_n = f(n)$ are called the terms of the sequence, n is called the index. When a_n is given by a formula, we refer to it as the general term.

Example: 1) $a_n = 1 - \frac{1}{n}$, $n \geq 1$: $0, \frac{1}{2}, \frac{2}{3}, \frac{3}{4}, \frac{4}{5}, \dots$

2) $a_n = (-1)^n n$, $n \geq 0$: $0, -1, 2, -3, 4, \dots$

Example: Compute a_2, a_3, a_4 for the sequence defined recursively by $a_1 = 1$, $a_n = \frac{1}{2} \left(a_{n-1} + \frac{2}{a_{n-1}} \right)$.

$$a_2 = \frac{1}{2} \left(a_1 + \frac{2}{a_1} \right) = \frac{1}{2} \left(1 + \frac{2}{1} \right) = \frac{3}{2}$$

$$a_3 = \frac{1}{2} \left(a_2 + \frac{2}{a_2} \right) = \frac{1}{2} \left(\frac{3}{2} + \frac{2}{\frac{3}{2}} \right) = \frac{17}{12}$$

$$a_4 = \frac{1}{2} \left(a_3 + \frac{2}{a_3} \right) = \frac{1}{2} \left(\frac{17}{12} + \frac{2}{\frac{17}{12}} \right) = \frac{577}{408}$$

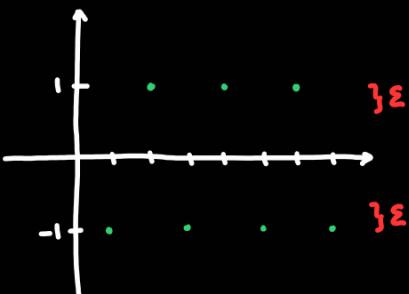
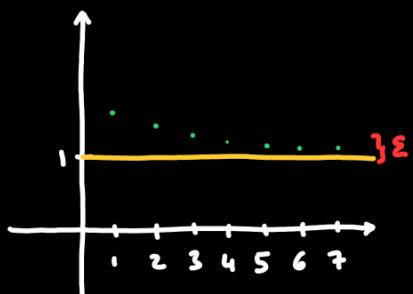
Limit of a sequence:

We say that $\{a_n\}$ converges to a limit L , and we write $\lim_{n \rightarrow \infty} a_n = L$, if for every

$\epsilon > 0$ there is a number M such that $|a_n - L| < \epsilon$ for all $n > M$.

If no limit exists, we say that $\{a_n\}$ diverges. If the terms increase without bound,

we say that $\{a_n\}$ diverges to infinity.



$$a_n = \frac{n+4}{n+1}$$

$$a_n = (-1)^n$$

Example: Let $a_n = \frac{n+4}{n+1}$. Prove that $\lim_{n \rightarrow \infty} a_n = 1$.

We have $|a_n - 1| = \left| \frac{n+4}{n+1} - 1 \right| = \frac{3}{n+1}$. Thus $|a_n - 1| < \varepsilon$ if $\frac{3}{n+1} < \varepsilon$, that is $n > \frac{3}{\varepsilon} - 1$.

Set $M = \frac{3}{\varepsilon} - 1$, now for $n > M$ we have:

$$|a_n - 1| = \left| \frac{n+4}{n+1} - 1 \right| = \frac{3}{n+1} < 3 \cdot \frac{1}{\frac{3}{\varepsilon} - 1 + 1} = 3 \cdot \frac{1}{\frac{3}{\varepsilon}} = \varepsilon. \text{ Hence } \lim_{n \rightarrow \infty} a_n = 1.$$

Sequence defined by a function:

If $\lim_{x \rightarrow \infty} f(x)$ exists, then the sequence $a_n = f(n)$ converges to the same limit.

$$\boxed{\lim_{n \rightarrow \infty} a_n = \lim_{x \rightarrow \infty} f(x).}$$

Example: Find the limit of the sequence with general term $a_n = \frac{n^2 - 2}{n^2}$.

Note that $a_n = \frac{n^2 - 2}{n^2} = 1 - \frac{2}{n^2}$, consider $f(x) = 1 - \frac{2}{x^2}$, now:

$$\lim_{n \rightarrow \infty} a_n = \lim_{x \rightarrow \infty} f(x) = \lim_{x \rightarrow \infty} \left(1 - \frac{2}{x^2} \right) = 1.$$

Example: Calculate:

$$\lim_{n \rightarrow \infty} \frac{n + \ln(n)}{n^2} = \lim_{x \rightarrow \infty} \frac{x + \ln(x)}{x^2} \stackrel{\text{L'Hôpital's Rule}}{\longrightarrow} \lim_{x \rightarrow \infty} \frac{1 + \frac{1}{x}}{2x} = 0.$$

Example: Compute for $r \geq 0$ and $c > 0$:

$$\lim_{n \rightarrow \infty} c \cdot c^n = \lim_{n \rightarrow \infty} c \cdot c^x = c \cdot \lim_{x \rightarrow \infty} c^x = \begin{cases} 0 & \text{if } 0 \leq c < 1, \\ \infty & \text{if } c = 1, \\ \text{does not exist} & \text{if } c > 1. \end{cases}$$

$$\begin{array}{ccc} n \rightarrow \infty & x \rightarrow \infty & x \rightarrow \infty \\ \lim_{n \rightarrow \infty} a_n = L & \lim_{x \rightarrow \infty} a_x = L & \lim_{x \rightarrow \infty} a_x = L \\ \lim_{n \rightarrow \infty} b_n = M & \lim_{x \rightarrow \infty} b_x = M & \lim_{x \rightarrow \infty} b_x = M \\ \lim_{n \rightarrow \infty} c_n = C & \lim_{x \rightarrow \infty} c_x = C & \lim_{x \rightarrow \infty} c_x = C \end{array} \quad \left\{ \begin{array}{l} L + M \text{ if } r < 1 \\ \infty \text{ if } r > 1. \end{array} \right.$$

Limit laws for sequences:

Assume that $\{a_n\}$ and $\{b_n\}$ are convergent sequences with $\lim_{n \rightarrow \infty} a_n = L$, $\lim_{n \rightarrow \infty} b_n = M$.

$$\lim_{n \rightarrow \infty} (a_n \pm b_n) = \lim_{n \rightarrow \infty} a_n \pm \lim_{n \rightarrow \infty} b_n = L \pm M.$$

$$\lim_{n \rightarrow \infty} a_n b_n = (\lim_{n \rightarrow \infty} a_n)(\lim_{n \rightarrow \infty} b_n) = LM.$$

$$\lim_{n \rightarrow \infty} \frac{a_n}{b_n} = \frac{\lim_{n \rightarrow \infty} a_n}{\lim_{n \rightarrow \infty} b_n} = \frac{L}{M} \text{ if } M \neq 0.$$

$$\lim_{n \rightarrow \infty} c \cdot a_n = c \cdot \lim_{n \rightarrow \infty} a_n = c \cdot L \text{ for any constant } c.$$

Squeeze theorem for sequences:

Let $\{a_n\}$, $\{b_n\}$, $\{c_n\}$ be sequences such that for some number M ,

$$b_n \leq a_n \leq c_n \text{ for } n > M \text{ and } \lim_{n \rightarrow \infty} b_n = L = \lim_{n \rightarrow \infty} c_n. \text{ Then } \lim_{n \rightarrow \infty} a_n = L.$$

Example: Show that if $\lim_{n \rightarrow \infty} |a_n| = 0$, then $\lim_{n \rightarrow \infty} a_n = 0$.

We have $-|a_n| \leq a_n \leq |a_n|$, and we have $\lim_{n \rightarrow \infty} -|a_n| = -\lim_{n \rightarrow \infty} |a_n| = 0$, so by the

Squeeze theorem we have $\lim_{n \rightarrow \infty} a_n = 0$.

Example: Compute for $r < 0$ and $c \neq 0$:

$$\lim_{n \rightarrow \infty} c \cdot r^n = \begin{cases} 0 & \text{if } -1 < r < 0. \\ \infty & \text{if } r < -1. \end{cases}$$

(diverges if $r \leq -1$.)

If $-1 < r < 0$, then $0 < |r| < 1$ and $\lim_{n \rightarrow \infty} |cr^n| = \lim_{n \rightarrow \infty} |c| \cdot |r^n| = 0$. Thus $\lim_{n \rightarrow \infty} cr^n = 0$ by

the Squeeze theorem.

If $r = -1$ then the sequence $a_n = cr^n = (-1)^n c$ alternates in sign and does not approach a limit.

If $r < -1$ then $a_n = cr^n$ alternates in sign and $|a_n| = |cr^n|$ grows arbitrarily large and does not approach a limit.

Example: Prove that $\lim_{n \rightarrow \infty} \frac{R^n}{n!} = 0$ for all R .

Assume that $R > 0$ and let M be the positive integer such that $M \leq R < M+1$. For

$n > M$ we write: $\frac{R^n}{n!} = \underbrace{\left(\frac{R}{1} \cdot \frac{R}{2} \cdots \frac{R}{M}\right)}_C \cdot \underbrace{\frac{R}{M+1}}_{\leq 1} \cdot \underbrace{\frac{R}{M+2}}_{\leq 1} \cdots \underbrace{\frac{R}{n-1} \cdot \frac{R}{n}}_{\leq 1} \leq C \cdot \frac{R}{n}$. Thus:

$0 \leq \frac{R^n}{n!} \leq C \cdot \frac{R}{n}$, and since $\lim_{n \rightarrow \infty} C \cdot \frac{R}{n} = 0$, by the Squeeze theorem we have

$\lim_{n \rightarrow \infty} \frac{R^n}{n!} = 0$ as claimed.

If $R < 0$, we have that $|\frac{R^n}{n!}|$ tends to zero, so $\lim_{n \rightarrow \infty} \frac{R^n}{n!} = 0$.

If $R = 0$, then $\lim_{n \rightarrow \infty} \frac{R^n}{n!} = \lim_{n \rightarrow \infty} 0 = 0$.

We can bring a limit inside a continuous function.

If $f(x)$ is continuous and $\lim_{n \rightarrow \infty} a_n = L$, then $\lim_{n \rightarrow \infty} f(a_n) = f\left(\lim_{n \rightarrow \infty} a_n\right) = f(L)$.

Example: Compute $\lim_{n \rightarrow \infty} f(a_n)$ for $a_n = \frac{3n}{n+1}$ and $f(x) = x^2$.

$$\lim_{n \rightarrow \infty} f(a_n) = \lim_{n \rightarrow \infty} \left(\frac{3n}{n+1} \right)^2 = f \left(\lim_{n \rightarrow \infty} \frac{3n}{n+1} \right) = \left(\lim_{n \rightarrow \infty} \frac{3n}{n+1} \right)^2 = 3^2 = 9.$$

Bounded sequences: A sequence $\{a_n\}$ is:

Bounded from above if there is a number M such that $a_n \leq M$ for all n . The number

M is called an upper bound.

Bounded from below if there is a number m such that $a_n \geq m$ for all n . The number

m is called a lower bound.

Convergent sequences are bounded:

If $\{a_n\}$ converges, then $\{a_n\}$ is bounded.

Bounded monotonic sequences converge:

If $\{a_n\}$ is increasing and $a_n \leq M$, then $\{a_n\}$ converges and $\lim_{n \rightarrow \infty} a_n \leq M$.

If $\{a_n\}$ is decreasing and $a_n \geq m$, then $\{a_n\}$ converges and $\lim_{n \rightarrow \infty} a_n \geq m$.

Example: Does $\lim_{n \rightarrow \infty} (\sqrt{n+1} - \sqrt{n})$ exist?

We have $a_n = \sqrt{n+1} - \sqrt{n}$, so consider $f(x) = \sqrt{x+1} - \sqrt{x}$. This function is decreasing because

its derivative is negative: $f'(x) = \frac{1}{2\sqrt{x+1}} - \frac{1}{2\sqrt{x}} < 0$ for $x > 0$. Then $a_n = f(n)$ is decreasing.

Moreover $a_n > 0$ for all n , so $m = 0$ is a lower bound for the sequence. Since a bounded monotonic sequence converges, $\lim_{n \rightarrow \infty} (\sqrt{a_{n+1}} - \sqrt{a_n})$ exists. Note:

$$\sqrt{a_{n+1}} - \sqrt{a_n} = (\sqrt{a_{n+1}} - \sqrt{a_n}) \cdot \frac{\sqrt{a_{n+1}} + \sqrt{a_n}}{\sqrt{a_{n+1}} + \sqrt{a_n}} = \frac{a_{n+1} - a_n}{\sqrt{a_{n+1}} + \sqrt{a_n}} = \frac{1}{\sqrt{a_{n+1}} + \sqrt{a_n}}, \text{ and now:}$$

$$\lim_{n \rightarrow \infty} a_n = \lim_{n \rightarrow \infty} \sqrt{a_{n+1}} - \sqrt{a_n} = \lim_{n \rightarrow \infty} \frac{1}{\sqrt{a_{n+1}} + \sqrt{a_n}} = \lim_{x \rightarrow \infty} \frac{1}{\sqrt{x+1} + \sqrt{x}} = 0.$$

Section 11.2.: Summing an infinite series.

An infinite series is an infinite sum: $\sum \frac{1}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \dots$. We compute the sum of

an infinite series as the limit of its partial sums.

Infinite series: $a_1 + a_2 + a_3 + a_4 + \dots$

N -th partial sum: $S_N = a_1 + a_2 + \dots + a_N = \sum_{n=1}^N a_n$.

If the series begins at k , then $S_N = \sum_{n=k}^N a_n$.

Convergence of an infinite series:

An infinite series $\sum_{n=k}^{\infty} a_n$ converges to the sum S if its partial sums converge to S :

$\lim_{N \rightarrow \infty} S_N = S$. In this case, we write $S = \sum_{n=k}^{\infty} a_n$.

If the limit does not exist, we say that the infinite series diverges.

If the limit is infinite, we say that the infinite series diverges to infinity.

Example: Telescopic series. Compute $S = \sum_{n=1}^{\infty} \frac{1}{n(n+1)} = 1$.

We compute the partial sums using that $\frac{1}{n(n+1)} = \frac{1}{n} - \frac{1}{n+1}$:

$$S_1 = \frac{1}{1 \cdot 2} = 1 - \frac{1}{2}$$

$$S_2 = \frac{1}{1 \cdot 2} + \frac{1}{2 \cdot 3} = \left(1 - \frac{1}{2}\right) + \left(\frac{1}{2} - \frac{1}{3}\right) = 1 - \frac{1}{3}$$

$$S_3 = \frac{1}{1 \cdot 2} + \frac{1}{2 \cdot 3} + \frac{1}{3 \cdot 4} = \left(1 - \frac{1}{2}\right) + \left(\frac{1}{2} - \frac{1}{3}\right) + \left(\frac{1}{3} - \frac{1}{4}\right) = 1 - \frac{1}{4}, \text{ and in general:}$$

$$S_N = \left(1 - \frac{1}{2}\right) + \left(\frac{1}{2} - \frac{1}{3}\right) + \cdots + \left(\frac{1}{N} - \frac{1}{N+1}\right) = 1 - \frac{1}{N+1}$$

Now, the sum S is the limit of the partial sums:

$$S = \lim_{N \rightarrow \infty} S_N = \lim_{N \rightarrow \infty} \left(1 - \frac{1}{N}\right) = 1$$

It is important to keep in mind the difference between a sequence $\{a_n\}$ and an infinite

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

Linearity of infinite series:

If $\sum a_n$ and $\sum b_n$ converge, then $\sum (a_n \pm b_n)$ and $\sum c a_n$ also converge (for c any constant), and:

$$\sum a_n + \sum b_n = \sum (a_n + b_n), \quad \sum a_n - \sum b_n = \sum (a_n - b_n), \quad \sum c a_n = c \sum a_n$$

Sum of a geometric series: Let $c \neq 0$. If $|r| < 1$ then:

$$\sum_{n=0}^{\infty} c r^n = c + c r + c r^2 + \cdots = \frac{c}{1-r} \quad \text{and} \quad \sum_{n=M}^{\infty} c r^n = c r^M + c r^{M+1} + c r^{M+2} + \cdots = \frac{c r^M}{1-r}$$

If $|r| \geq 1$ then the geometric series diverges.

Example: Compute:

$$\sum_{n=0}^{\infty} \frac{2+3^n}{5^n} = \sum_{n=0}^{\infty} \frac{2}{5^n} + \sum_{n=0}^{\infty} \frac{3^n}{5^n} = 2 \cdot \sum_{n=0}^{\infty} \frac{1}{5^n} + \sum_{n=0}^{\infty} \left(\frac{3}{5}\right)^n = 2 \cdot \frac{1}{1-\frac{1}{5}} + \frac{1}{1-\frac{3}{5}} = 2 \cdot \frac{5}{4} + \frac{5}{2} = 5.$$

Divergence test:

If the n -th term a_n does not converge to zero, then the series $\sum_{n=1}^{\infty} a_n$ diverges.

Example: Prove the divergence of $\sum_{n=1}^{\infty} \frac{n}{4n+1}$.

We have $\lim_{n \rightarrow \infty} a_n = \lim_{n \rightarrow \infty} \frac{n}{4n+1} = \lim_{n \rightarrow \infty} \frac{1}{4 + \frac{1}{n}} = \lim_{x \rightarrow \infty} \frac{1}{4 + \frac{1}{x}} = \frac{1}{4}$. Since the general term does

not converge, the series diverge.

Example: Prove the divergence of $\sum_{n=1}^{\infty} \frac{1}{\sqrt{n}}$.

Note that the general term $a_n = \frac{1}{\sqrt{n}}$ tends to zero. However:

$$S_N = \frac{1}{\sqrt{1}} + \frac{1}{\sqrt{2}} + \cdots + \frac{1}{\sqrt{N}} \geq \frac{1}{\sqrt{N}} + \frac{1}{\sqrt{N}} + \cdots + \frac{1}{\sqrt{N}} = N \cdot \frac{1}{\sqrt{N}} = \sqrt{N}$$

\uparrow
 $\frac{1}{\sqrt{n}} \geq \frac{1}{\sqrt{N}}$ for $n \leq N$.

So $\lim_{N \rightarrow \infty} S_N \geq \lim_{N \rightarrow \infty} \sqrt{N} = \infty$, and the series diverges.

Section 11.3.: Convergence of series with positive terms.

We consider positive series, namely series $\sum a_n$ where $a_n > 0$ for all n .



We can visualize the terms of a positive series



as rectangles of height a_n and width 1.

The partial sum $S_N = a_1 + \dots + a_N$ is the area of the first N rectangles. Since $a_{N+1} > 0$ then

$S_N < S_{N+1}$ so the partial sums form an increasing sequence.

Dichotomy for positive series:

For $S = \sum a_n$ a positive series we have either:

(i) The partial sums s_n are bounded above and S converges.

(ii) The partial sums s_n are not bounded above and S diverges.

Integral test:

Let $a_n = f(n)$ where $f(x)$ is positive, decreasing, and continuous for $x \geq 1$. Then:

(i) If $\int_1^\infty f(x)dx$ converges then $\sum_{n=1}^\infty a_n$ converges.

(ii) If $\int_1^\infty f(x)dx$ diverges then $\sum_{n=1}^\infty a_n$ diverges.

Example: The harmonic series $\sum_{n=1}^\infty \frac{1}{n}$ diverges: let $f(x) = \frac{1}{x}$, then $a_n = \frac{1}{n} = f(n)$, $f(x)$ is

positive, decreasing, and continuous for $x \geq 1$. Then since:

$$\int_1^\infty f(x)dx = \int_1^\infty \frac{1}{x} dx = \lim_{R \rightarrow \infty} \int_1^R \frac{1}{x} dx = \lim_{R \rightarrow \infty} \ln(R) = \infty$$

the series $\sum_{n=1}^\infty \frac{1}{n}$ diverges by the integral test.

Ex 1: Does $\sum_{n=1}^\infty \frac{n}{\sqrt{n+1}}$ converge or diverge?

Example: Does $\sum_{n=1}^{\infty} \frac{1}{(n^2+1)^2}$ converge or diverge?

The function $f(x) = \frac{x}{(x^2+1)^2}$ is positive and continuous for $x \geq 1$. Moreover:

$f'(x) = \frac{1-3x^2}{(x^2+1)^3} < 0$ for $x \geq 1$, so $f(x)$ is decreasing. Then since:

$$\int_1^{\infty} f(x) dx = \int_1^{\infty} \frac{x dx}{(x^2+1)^2} = \lim_{R \rightarrow \infty} \int_1^R \frac{x dx}{(x^2+1)^2} = \lim_{R \rightarrow \infty} \frac{1}{2} \int_2^R \frac{du}{u^2} = \lim_{R \rightarrow \infty} \left[-\frac{1}{2u} \right]_2^R =$$

$u = x^2 + 1$
 $du = 2x dx$

$= \lim_{R \rightarrow \infty} \left(\frac{1}{4} - \frac{1}{2R} \right) = \frac{1}{4}$, by the integral test the series $\sum_{n=1}^{\infty} \frac{1}{(n^2+1)^2}$ converges.

Convergence of p-series:

The infinite series $\sum_{n=1}^{\infty} \frac{1}{n^p}$ converges if $p > 1$ and diverges if $p \leq 1$.

If $p \leq 0$ then the general term $a_n = n^{-p}$ does not tend to zero, so the series diverges.

If $p > 0$ then $f(x) = \frac{1}{x^p}$ is positive, decreasing, and continuous for $x \geq 1$. Since:

$$\int_1^{\infty} \frac{1}{x^p} dx = \begin{cases} \frac{1}{p-1} & \text{if } p > 1 \\ \infty & \text{if } p \leq 1 \end{cases}$$

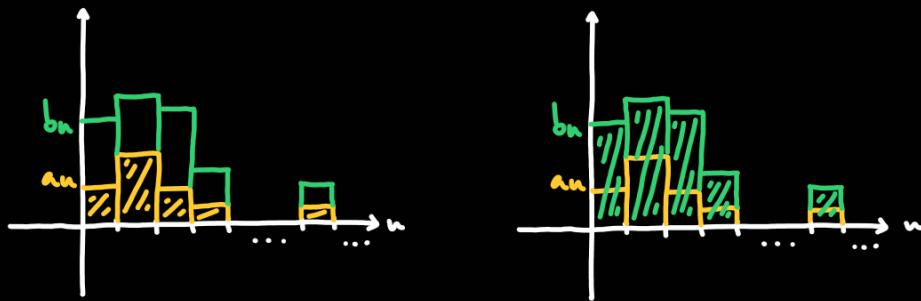
then by the integral test $\sum_{n=1}^{\infty} \frac{1}{n^p}$ converges for $p > 1$ and diverges for $p \leq 1$.

Comparison test:

Assume there exists $M > 0$ such that $0 \leq a_n \leq b_n$ for all $n > M$.

(i) If $\sum_{n=1}^{\infty} b_n$ converges then $\sum_{n=1}^{\infty} a_n$ converges.

(ii) If $\sum_{n=1}^{\infty} a_n$ diverges then $\sum_{n=1}^{\infty} b_n$ diverges.



Example: Does $\sum_{n=1}^{\infty} \frac{1}{\sqrt{n} 3^n}$ converge or diverge?

For $n \geq 1$ we have $\frac{1}{\sqrt{n} 3^n} \leq \frac{1}{3^n}$. Moreover $\sum_{n=1}^{\infty} \frac{1}{3^n}$ converges because it is a geometric series

with $r = \frac{1}{3} < 1$. By the Comparison Test, the smaller series $\sum_{n=1}^{\infty} \frac{1}{\sqrt{n} 3^n}$ converges.

Example: Does $\sum_{n=2}^{\infty} \frac{1}{(n^2+3)^{\frac{1}{3}}}$ converge or diverge?

We observe that $\frac{1}{(n^2+3)^{\frac{1}{3}}}$ behaves like $\frac{1}{n^{2/3}}$ when n goes to infinity. Since

$\frac{1}{n} \leq \frac{1}{n^{2/3}}$, we would like to prove that $\frac{1}{n} \leq \frac{1}{(n^2+3)^{\frac{1}{3}}}$. This inequality is equivalent to

$n^2+3 \leq n^3$. Consider $f(x) = x^3 - (x^2 - 3)$, which is positive for $x \geq 2$. Since:

$f'(x) = 3x^2 - 2x = 3x(x - \frac{2}{3}) > 0$ for $x \geq 2$, then $f(x)$ is increasing. Moreover $f(2) = 1$,

so $f(x) \geq 1 \geq 0$ for all $x \geq 2$, so $x^3 - (x^2 - 3) \geq 0$ for all $x \geq 2$, so $n^3 - (n^2 - 3) \geq 0$ for

all $n \geq 2$, so $\frac{1}{n} \leq \frac{1}{(n^2+3)^{\frac{1}{3}}}$ for all $n \geq 2$. Now $\sum_{n=2}^{\infty} \frac{1}{n}$ diverges, so by the Comparison

test $\sum_{n=2}^{\infty} \frac{1}{(n^2+3)^{\frac{1}{3}}}$ also diverges.

Example: Does $\sum_{n=2}^{\infty} \frac{1}{n(\ln(n))^2}$ converge or diverge?

We have $\frac{1}{n(\ln(n))^2} \leq \frac{1}{n}$ for $n \geq 3$, so we can compare $\sum_{n=3}^{\infty} \frac{1}{n(\ln(n))^2}$ with $\sum_{n=3}^{\infty} \frac{1}{n}$.

However the harmonic series diverges, and the Comparison test does not give information about the smaller series. Using the integral test, we have:

$$\int_2^{\infty} \frac{dx}{x(\ln(x))^2} = \int_{\ln(2)}^{\infty} \frac{du}{u^2} = \lim_{R \rightarrow \infty} \int_{\ln(2)}^R \frac{du}{u^2} = \lim_{R \rightarrow \infty} \left[-\frac{1}{u} \right]_{\ln(2)}^R = \lim_{R \rightarrow \infty} \left(\frac{1}{\ln(2)} - \frac{1}{R} \right) = \frac{1}{\ln(2)}$$

$u = \ln(x), du = \frac{1}{x} dx$

and the infinite series converges.

Limit comparison test:

Let $\{a_n\}$ and $\{b_n\}$ be positive sequences such that $L = \lim_{n \rightarrow \infty} \frac{a_n}{b_n}$ exists.

If $L > 0$ then $\sum a_n$ converges if and only if $\sum b_n$ converges.

If $L = \infty$ and $\sum a_n$ converges then $\sum b_n$ converges.

If $L = 0$ and $\sum b_n$ converges then $\sum a_n$ converges.

Example: Does $\sum_{n=2}^{\infty} \frac{n^2}{n^4-n-1}$ converge or diverge?

Let $a_n = \frac{n^2}{n^4-n-1}$ and $b_n = \frac{1}{n^2}$, now:

$$\lim_{n \rightarrow \infty} \frac{a_n}{b_n} = \lim_{n \rightarrow \infty} \frac{n^2}{n^4-n-1} \cdot \frac{n^2}{1} = \lim_{n \rightarrow \infty} \frac{1}{1-n^{-3}-n^{-4}} = 1.$$

Since $\sum_{n=2}^{\infty} \frac{1}{n^2}$ is a converging p-series, then $\sum_{n=2}^{\infty} \frac{n^2}{n^4-n-1}$ also converges by limit comparison.

Example: Does $\sum_{n=3}^{\infty} \frac{1}{\sqrt{n^2+4}}$ converge or diverge?

Let $a_n = \frac{1}{\sqrt{n^2+4}}$ and $b_n = \frac{1}{n}$, now:

$$\lim_{n \rightarrow \infty} \frac{a_n}{b_n} = \lim_{n \rightarrow \infty} \frac{n}{\sqrt{n^2+4}} = \lim_{n \rightarrow \infty} \frac{1}{\sqrt{1 + \frac{4}{n^2}}} = 1.$$

Since $\sum_{n=3}^{\infty} \frac{1}{n}$ is a diverging p-series, then $\sum_{n=3}^{\infty} \frac{1}{\sqrt{n^2+4}}$ also diverges by the limit comparison test.