Warm up

1. From last time, what is the equation for...
   (a) ...the distance traveled by a ball dropped, as a function of time?

   $$f(t) = 4.9t^2$$

   (b) ...the velocity of a ball dropped, as a function of time?

   $$v(t) = 9.8t$$

2. If a ball is dropped, how long does it take for its speed to reach 20 meters/second?

   Solve $20 = v(t) = 9.8t$ for t

   $$t = 20/9.8$$

3. How far has the ball traveled by the time it reaches that speed?

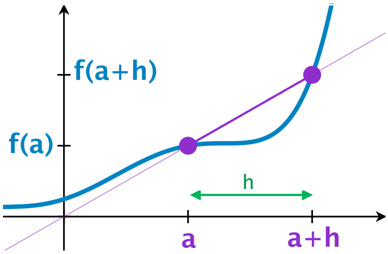
   $$f(20/9.8) = 4.9 * (20/9.8)^2$$

Limits

From last time...

Let $y = f(t)$ be a function that gives the position at time t of an object moving along the y-axis. Then

$$\begin{aligned} \text{Ave vel}[t_1, t_2] &= \frac{f(t_2) - f(t_1)}{t_2 - t_1} \\ \text{Velocity}(t) &= \lim_{h \to 0} \frac{f(t+h) - f(t)}{h}. \end{aligned}$$



We need to be able to take limits!

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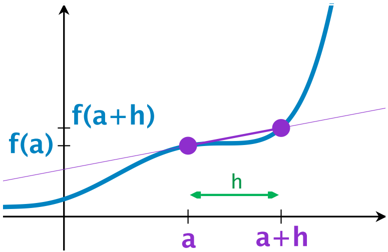

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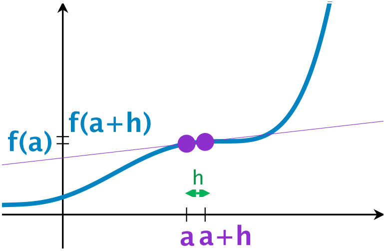


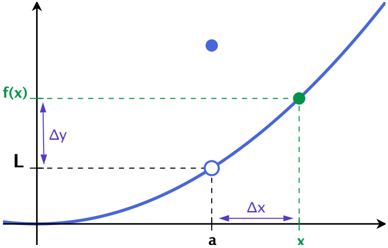
We need to be able to take limits!

Limit of a Function – Definition

We say that a function f *approaches the limit* L as x approaches a,

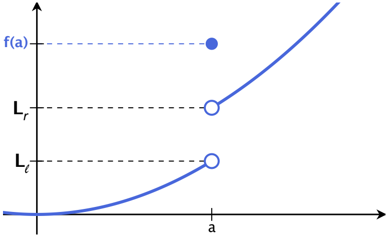
$$\text{written} \qquad \lim_{x \to a} f(x) = L,$$

if we can make $f(x)$ as close to L as we want by taking x sufficiently close to a.



i.e. If you need Δy to be smaller,
you only need to make Δx smaller
(Δ means "change")

One-sided limits



Right-handed limit: $L_r = \lim_{x \to a^+} f(x)$

if $f(x)$ gets closer to L_r as x gets closer to *a from the right*

Left-handed limit: $L_\ell = \lim_{x \to a^-} f(x)$

if $f(x)$ gets closer to L_ℓ as x gets closer to *a from the left*

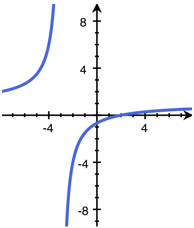
Theorem

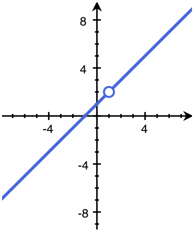
The limit of f as $x \to a$ exists if and only if both the right-hand and left-hand limits exist and have the same value, i.e.

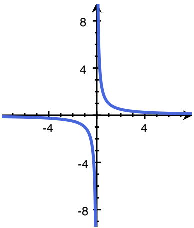
$$\lim_{x \to a} f(x) = L \textit{ if and only if } \lim_{x \to a^-} f(x) = L \textit{ and } \lim_{x \to a^+} f(x) = L.$$

Examples

$$\lim_{x \to 2} \frac{x-2}{x+3} = 0 \qquad \lim_{x \to 1} \frac{x^2-1}{x-1} = 2 \qquad \lim_{x \to 0} \frac{1}{x} \text{ is undefined}$$







Theorem

If $\lim_{x\to a} f(x) = A$ *and* $\lim_{x\to a} g(x) = B$ *both exist, then*

1. $\lim_{x\to a}(f(x) + g(x)) = \lim_{x\to a} f(x) + \lim_{x\to a} g(x) = A + B$
2. $\lim_{x\to a}(f(x) - g(x)) = \lim_{x\to a} f(x) - \lim_{x\to a} g(x) = A - B$
3. $\lim_{x\to a}(f(x)g(x)) = \lim_{x\to a} f(x) \cdot \lim_{x\to a} g(x) = A \cdot B$
4. $\lim_{x\to a}(f(x)/g(x)) = \lim_{x\to a} f(x)/\lim_{x\to a} g(x) = A/B$ $(B \neq 0)$.

In short: to take a limit

Step 1: Can you just plug in? If so, do it.

Step 2: If not, is there some sort of algebraic manipulation (like cancellation) that can be done to fix the problem? If so, do it. Then plug in.

Step 3: Learn some special limit to fix common problems. (Later)

If in doubt, graph it!

Examples

1. $\lim_{x\to 2} \dfrac{x-2}{x+3} = \boxed{0}$ because if $f(x) = \frac{x-2}{x+3}$, then $f(2) = 0$.
2. $\lim_{x\to 1} \dfrac{x^2-1}{x-1} \begin{smallmatrix}\to 0\\ \to 0\end{smallmatrix}$

   If $f(x) = \frac{x^2-1}{x-1}$, then $f(x)$ is undefined at $x = 1$.
   However, so long as $x \neq 1$,

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

   So

   $$\lim_{x\to 1} \frac{x^2-1}{x-1} = \lim_{x\to 1} x+1 = 1+1 = \boxed{2}.$$

3. $\lim_{x\to 0} \dfrac{\sqrt{x+2}-\sqrt{2}}{x} \begin{smallmatrix}\to 0\\ \to 0\end{smallmatrix}$, so again, $f(x)$ is undefined at a.

Examples

3. $\lim_{x\to 0} \frac{\sqrt{x+2}-\sqrt{2}}{x} \begin{smallmatrix}\to 0\\ \to 0\end{smallmatrix}$, so again, $f(x)$ is undefined at a.

Multiply top and bottom by the *conjugate*:

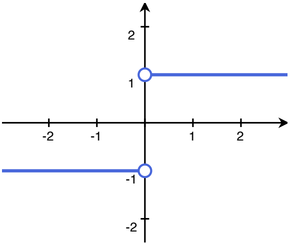
$$\begin{aligned}\lim_{x\to 0} \frac{\sqrt{x+2}-\sqrt{2}}{x} &= \lim_{x\to 0} \left(\frac{\sqrt{x+2}-\sqrt{2}}{x}\right)\left(\frac{\sqrt{x+2}+\sqrt{2}}{\sqrt{x+2}+\sqrt{2}}\right)\\ &= \lim_{x\to 0} \frac{x+2-2}{x(\sqrt{x+2}+\sqrt{2})} \qquad \text{since } (a-b)(a+b)=a^2-b^2\\ &= \lim_{x\to 0} \frac{x}{x(\sqrt{x+2}+\sqrt{2})}\\ &= \lim_{x\to 0} \frac{1}{\sqrt{x+2}+\sqrt{2}} = \boxed{\frac{1}{2\sqrt{2}}}\end{aligned}$$

Examples

1. $\lim_{x\to 1} \frac{x^2-3x+2}{x^2+4x-5}$ $= \boxed{-\frac{1}{6}}$

2. $\lim_{x\to -2} \frac{|x|}{x} = \boxed{-1}$

3. $\lim_{x\to 0} \frac{|x|}{x}$ is $\boxed{\text{undefined}}$



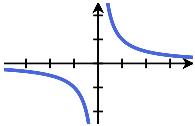
4. $$\lim_{x\to 0} \frac{(3+x)^2 - 3^2}{x}$$ $= \boxed{6}$

Infinite limits

If $f(x)$ gets arbitrarily large as $x \to a$, then it doesn't have a limit. Sometimes, though, it's more useful to give more information.

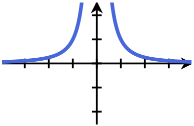
Example:

For both $f(x) = \frac{1}{x}$ and $f(x) = \frac{1}{x^2}$, $\lim_{x\to 0} f(x)$ does not exist. However, they're both "better behaved" than that might imply:



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

$$\lim_{x\to 0} \frac{1}{x} \text{ does not exist}$$



$$\lim_{x\to 0^+} \frac{1}{x^2} = \infty, \lim_{x\to 0^-} \frac{1}{x^2} = \infty$$

$$\lim_{x\to 0} \frac{1}{x^2} = \infty$$

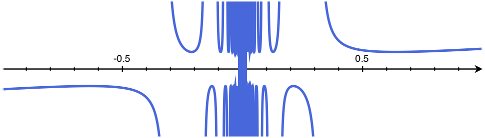
Why? A *vertical asymptote* occurs where

$$\lim_{x\to a^+} f(x) = \pm\infty \quad \text{and} \quad \lim_{x\to a^-} f(x) = \pm\infty$$

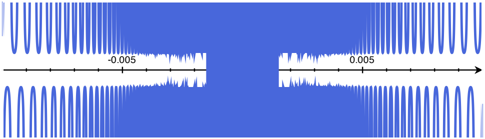
Infinite limits

Badly behaved example:

$$f(x) = \csc(1/x)$$



Zoom way in:



(denser and denser vertical asymptotes)

$\lim_{x\to 0^+} \csc(1/x)$ does not exist, and $\lim_{x\to 0^-} \csc(1/x)$ does not exist

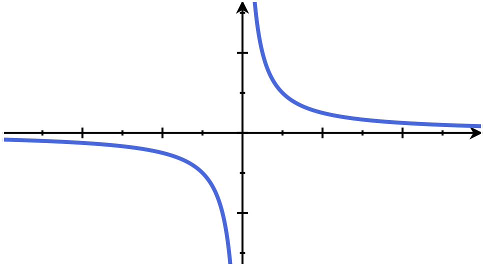
Limits at Infinity

We say that a function f *approaches the limit* L as x gets bigger and bigger (in the positive or negative direction),

$$\text{written} \qquad \lim_{x\to\infty} f(x) = L \quad \text{or} \quad \lim_{x\to-\infty} f(x) = L$$

if we can make $f(x)$ as close to L as we want by taking x sufficiently large. *(By "large", we mean large in magnitude)*

Example 1:



$$\lim_{x\to-\infty} \frac{1}{x} = 0 \qquad \text{and} \qquad \lim_{x\to\infty} \frac{1}{x} = 0.$$

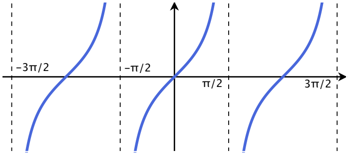
Limits at Infinity: functions and their inverses

Theorem

If $\lim_{x\to a^\pm} f(x) = \infty$, *then* $\lim_{x\to\infty} f^{-1}(x) = a$.
If $\lim_{x\to a^\pm} f(x) = -\infty$, *then* $\lim_{x\to-\infty} f^{-1}(x) = a$.

Example: Let $\arctan(x)$ be the inverse function to $\tan(x)$:

$y = \tan(x)$:



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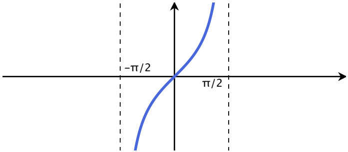

(restrict the domain to $(-\frac{\pi}{2}, \frac{\pi}{2})$ so that we can invert)

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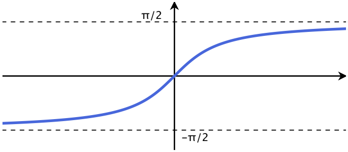

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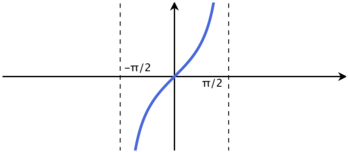

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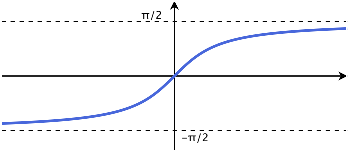
Since $\lim_{x\to\pi/2^-} = \infty$
and $\lim_{x\to -\pi/2^+} = -\infty$

$y = \arctan(x)$:



we have $\lim_{x\to\infty} = \pi/2$
and $\lim_{x\to -\infty} = -\pi/2$

Rational functions

Limits that look like they're going to $\frac{\infty}{\infty}$ can actually be doing lots of different things. To fix this, divide the top and bottom by the highest power in the denominator!

Ex 1 $\lim_{x\to\infty} \frac{x-1}{x^3+2} \begin{smallmatrix}\to\infty\\ \to\infty\end{smallmatrix}$

Fix: multiply the expression by $\frac{1/x^3}{1/x^3}$:

$$\lim_{x\to\infty} \frac{x-1}{x^3+2} = \lim_{x\to\infty} \left(\frac{x-1}{x^3+2}\right)\left(\frac{1/x^3}{1/x^3}\right) = \lim_{x\to\infty} \frac{\frac{1}{x^2}-\frac{1}{x^3}}{1+\frac{2}{x^3}} = \frac{0-0}{1+0} = \boxed{0}$$

Ex 2 $\lim_{x\to\infty} \frac{3x^2-2x+1}{4x^2-1} \begin{smallmatrix}\to\infty\\ \to\infty\end{smallmatrix}$

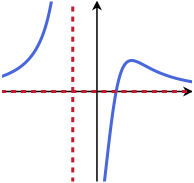
Fix: multiply the expression by $\frac{1/x^2}{1/x^2}$

Ex 3 $\lim_{x\to\infty} \frac{x^4-x^2+2}{x^3+3} \begin{smallmatrix}\to\infty\\ \to\infty\end{smallmatrix}$

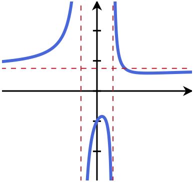
Fix: multiply the expression by $\frac{1/x^3}{1/x^3}$

Rational functions: quick trick

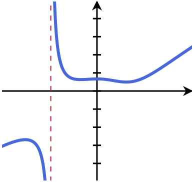
$$\lim_{x\to\infty} \frac{x-1}{x^3+2} = 0$$



$$\lim_{x\to\infty} \frac{3x^2-2x+1}{4x^2-1} = \frac{3}{4}$$



$$\lim_{x\to\infty} \frac{x^4-x^2+2}{x^3+3} = \infty$$



Suppose

$$P(x) = a_n x^n + \cdots + a_1 x + a_0 \quad \text{and} \quad Q(x) = b_m x^m + \cdots + b_1 x + b_0$$

are polynomials of degree n and m respectively. Then in general,

$$\lim_{x\to\infty} \frac{P(x)}{Q(x)} = \lim_{x\to\infty} \frac{a_n x^n}{b_m x^m} = \lim_{x\to\infty} \frac{a_n}{b_m} x^{n-m} = \begin{cases} 0 & n < m \\ \frac{a_n}{b_m} & n = m \\ \pm\infty & n < m \end{cases}$$

Examples: Other ratios with powers.

Example:

$$\lim_{x\to\infty} \frac{x}{\sqrt{3x^2+2}}$$

[hint: multiply by $\frac{1/x}{1/x}$ and remember $a\sqrt{b} = \sqrt{a^2 b}$.]

$$\begin{aligned}
\lim_{x\to\infty} \frac{x}{\sqrt{3x^2+2}} &= \lim_{x\to\infty} \left(\frac{x}{\sqrt{3x^2+2}}\right)\left(\frac{1/x}{1/x}\right) \\
&= \lim_{x\to\infty} \frac{1}{\frac{1}{x}\sqrt{3x^2+2}} \\
&= \lim_{x\to\infty} \frac{1}{\sqrt{\frac{1}{x^2}(3x^2+2)}} \\
&= \lim_{x\to\infty} \frac{1}{\sqrt{3+\frac{2}{x^2}}} \\
&= \frac{1}{\sqrt{3+0}} = \boxed{\frac{1}{\sqrt{3}}}
\end{aligned}$$