

CH 3 — Function Limits and Continuity

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Definitions

If $f : \mathbb{R} \rightarrow \mathbb{R}$ is a function and $a \in \mathbb{R}$, $\lim_{x \rightarrow a} f(x) = L$ if for all $\varepsilon > 0$ there exists $\delta > 0$ s.t. if $0 < |x - a| < \delta$, then $|f(x) - L| < \varepsilon$

Examples:

1) Prove using the $\varepsilon - \delta$ definition that $\lim_{x \rightarrow 0} f(x)$ DNE where

$$f(x) = \begin{cases} -2 & \text{if } x < 0 \\ 3 & \text{if } x > 0 \end{cases}$$

Domain: $\mathbb{R} \setminus \{0\}$

Take $\varepsilon = 1$. Consider some $\delta > 0$. Within $(0 - \delta, 0 + \delta)$

We have both $(-\delta, 0)$ where $f(x) = -2$ and $(0, \delta)$ where $f(x) = 3$. If this δ exists for $\varepsilon = 1$ then the limit L would need to be distance 1 or both -2 and 3, where is impossible.

$$\therefore \lim_{x \rightarrow 0} f(x) = \text{DNE}$$

2) $\lim_{x \rightarrow 7} 8x - 3 = 53$

Let $\varepsilon > 0$ be arbitrary.

We want find δ s.t. if $0 < |x - 7| < \delta$ then $|8x - 3 - 53| < \varepsilon \rightarrow \delta = \frac{\varepsilon}{8}$

Pick $\delta = \frac{\varepsilon}{8}$.

Then if $0 < |x - 7| < \frac{\varepsilon}{8}$, $|(8x - 3) - 53| = |8x - 56| = 8|x - 7| < 8 \cdot \frac{\varepsilon}{8} = \varepsilon$

3) $\lim_{x \rightarrow 1} x^2 + 3x + 4 = 8$

We want for any $\varepsilon > 0$ and $\delta > 0$: $|x - 1| < \delta$, then $|f(x) - L| < \varepsilon$

$$\Leftrightarrow |x^2 + 3x - 4| < \varepsilon \Leftrightarrow |(x + 4)(x - 1)| < \varepsilon \Leftrightarrow |x + 4| - |x - 1| < \varepsilon$$

I can always make δ smaller if I need to.

take $\delta < 1$, then $|x - 1| < 1 \Rightarrow 0 < x < 2$

$|x + 4| < 6 \rightarrow |x + 4||x - 1| < 6\delta$, but $6\delta < \varepsilon \Leftrightarrow \delta < \frac{\varepsilon}{6}$. Say $\frac{\varepsilon}{7} < \frac{\varepsilon}{6}$ for all epsilon.

Take $\delta < \min(1, \frac{\varepsilon}{6})$

Proof

Let $\varepsilon > 0$ be given. Take $\delta = \min(\frac{1}{2}, \frac{\varepsilon}{7})$. Then, if $|x - 1| < \delta$, $|x^2 + 3x + 4 - 8| = |x^2 + 3x - 4| = |(x + 4)(x - 1)| = |x + 4||x - 1| < 6 \cdot \frac{\varepsilon}{7} < \varepsilon$

□

**Info – Sequential Characterization of Limits Theorem**

Let $a \in \mathbb{R}$. let the function $f(x)$ be defined on an open interval containing a , except possibly at $x = a$ itself. Then the following are equivalent:

1. $\lim_{x \rightarrow a} f(x) = L$
2. For all sequences $\{x_n\}$ satisfying $\lim_{n \rightarrow \infty} x_n = a$ and $x_n \neq a, \forall n \in \mathbb{N}$, we have that $\lim_{n \rightarrow \infty} f(x_n) = L$

**Tip – Usage of Sequential Characterization of Limits**

1. Find a sequence $\{x_n\}$ with $x_n \rightarrow a$
2. Find two sequences $\{x_n\}, \{y_n\}$ with $x_n, y_n \rightarrow a$ and $x_n, y_n \neq a, \forall n \in \mathbb{N}$ but which $\{f(x_n)\}, \{f(y_n)\}$ converge to different values

Proof

\Rightarrow : $\lim_{x \rightarrow a} f(x) = L$ means $\forall \varepsilon > 0, \exists \delta > 0 : |x - a| < \delta$, then $|f(x) - L| < \varepsilon$.

Let $\{x_n\}$ be s.t. $x_n \rightarrow a$ (meaning that $\forall \varepsilon > 0, \exists N \in \mathbb{N} : \forall n > N, |x_n - a| < \varepsilon_2$) and $x_n \neq a$ for any n .

In particular, let ε for $x_n \rightarrow a$ be δ . Then $\forall n > N, |x_n - a| < \delta$, and so $|f(x_n) - L| < \varepsilon_1$. Then $\forall n > N, |x_n - a| < \delta$ and so $|f(x_n) - L| < \varepsilon_1$. So by definition, $\lim_{n \rightarrow \infty} f(x_n) = L$

Side Question: We saw the limit of a sequence is unique. Is the same true for limits of functions?

ANS: NO, it is like saying $\lim_{x \rightarrow a} f(x) = L$ and $= M$ and $L \neq M$ Suppose true. By Sequential Characterization of Limits, $\forall \{x_n\} \rightarrow a$ but $x_n \neq a \forall n, f(x_n) \rightarrow L$ and $f(x_n) \rightarrow M$ but $L \neq M$ Since the limits of sequences are unique, thus there is a contradiction.

Examples:


Prove that $\lim_{x \rightarrow 0} \cos\left(\frac{1}{x}\right)$ does not exist

We take sequences of peak points of $\cos\left(\frac{1}{x}\right)$, that is $-1, 1$. Then will converge to $-1, 1$ repeatedly, so by Sequential Characterization, $\lim_{x \rightarrow 0} \cos\left(\frac{1}{x}\right)$ will not exist.

$\cos\left(\frac{1}{x}\right) = 1$ if $x = \frac{1}{2k\pi}, k \in \mathbb{Z}$, and $\cos\left(\frac{1}{x}\right) = -1$ if $x = \frac{1}{(2k+1)\pi}, k \in \mathbb{Z}$.

Let $x_n = \frac{1}{2n\pi}$ and $y_n = \frac{1}{(2n+1)\pi}$. Then $x_n, y_n \rightarrow 0, x_n, y_n \neq 0 \forall n$. It converges to both -1 and 1 . By Sequential Characterization, the limit DNE.

Limit Laws

 **Info** — Let f, g be functions with $\lim_{x \rightarrow a} f(x) = L$, $\lim_{x \rightarrow a} g(x) = M$ for some $L, M \in \mathbb{R}$ then:

1. For any $c \in \mathbb{R}$, if $f(x) = c$ for all n then $L = c$
2. For any $c \in \mathbb{R}$, if $\lim_{x \rightarrow a} cf(x) = cL$
3. $\lim_{x \rightarrow a} (f(x) + g(x)) = L + M$
4. $\lim_{x \rightarrow a} f(x) \cdot g(x) = LM$
5. $\lim_{x \rightarrow a} \frac{f(x)}{g(x)} = \frac{L}{M}$ if $M \neq 0$
6. If $\alpha > 0$ and $L > 0$, then $\lim_{x \rightarrow a} f(x)^\alpha = L^\alpha$

Proof

We assume functions f, g are defined on a punctured neighborhood of a and $\lim_{x \rightarrow a} f(x) = L$, $\lim_{x \rightarrow a} g(x) = M$. In the quotient law we also assume $M \neq 0$.

1. Product law

Claim. $\lim_{x \rightarrow a} (f(x)g(x)) = LM$.

Proof. Let $\varepsilon > 0$. Then $|f(x)g(x) - LM| = |f(x)(g(x) - M) + M(f(x) - L)| \leq |f(x)| \cdot |g(x) - M| + |M| \cdot |f(x) - L|$.

Since $f(x) \rightarrow L$, choose $\delta_0 > 0$ with $|x - a| < \delta_0 \Rightarrow |f(x) - L| < 1$, hence $|f(x)| \leq |L| + 1$ there.

Choose $\delta_1, \delta_2 > 0$ so that $|x - a| < \delta_1 \Rightarrow |g(x) - M| < \frac{\varepsilon}{2(|L|+1)}$ and $|x - a| < \delta_2 \Rightarrow |f(x) - L| < \frac{\varepsilon}{2(|M|+1)}$.

Let $\delta = \min(\delta_0, \delta_1, \delta_2)$. For $0 < |x - a| < \delta$, $|f(x)g(x) - LM| \leq (|L| + 1) \cdot \frac{\varepsilon}{2(|L|+1)} + |M| \cdot \frac{\varepsilon}{2(|M|+1)} \leq \frac{\varepsilon}{2} + \frac{\varepsilon}{2} = \varepsilon$.

Thus $\lim_{x \rightarrow a} (fg) = LM$.

2. Quotient law (with $M \neq 0$)

Claim. $\lim_{x \rightarrow a} \frac{f(x)}{g(x)} = \frac{L}{M}$.

Proof. Let $\varepsilon > 0$. Because $g(x) \rightarrow M \neq 0$, there exists $\delta_0 > 0$ such that $|x - a| < \delta_0 \Rightarrow |g(x) - M| < |M|/2$, hence $|g(x)| \geq |M|/2$.

Now $|\frac{f(x)}{g(x)} - \frac{L}{M}| = |\frac{Mf(x) - Lg(x)}{g(x)M}| \leq \frac{|M| \cdot |f(x) - L| + |L| \cdot |g(x) - M|}{|M| \cdot |g(x)|} \leq \left(\frac{2}{|M|}\right) \cdot |f(x) - L| + \left(2 \cdot \frac{|L|}{|M|^2}\right) \cdot |g(x) - M|$.

Choose $\delta_1, \delta_2 > 0$ with $|x - a| < \delta_1 \Rightarrow |f(x) - L| < \left(|M|/4\right) \cdot \varepsilon$ and $|x - a| < \delta_2 \Rightarrow |g(x) - M| < \left(|M|^2/4(|L|+1)\right) \cdot \varepsilon$.

Let $\delta = \min(\delta_0, \delta_1, \delta_2)$. Then for $0 < |x - a| < \delta$, $|\frac{f(x)}{g(x)} - \frac{L}{M}| \leq \left(\frac{2}{|M|}\right) \cdot \left(|M|/4\right) \cdot \varepsilon + \left(2 \cdot \frac{|L|}{|M|^2}\right) \cdot \left(|M|^2/4(|L|+1)\right) \cdot \varepsilon \leq \frac{\varepsilon}{2} + \frac{\varepsilon}{2} = \varepsilon$.

Therefore $\lim_{x \rightarrow a} \frac{f(x)}{g(x)} = \frac{L}{M}$.

 **Info – Limit of Polynomial Functions** Let $p(x) = a_0 + a_1x + a_2x^2 + \dots + a_nx^n$ be a polynomial.

Then $\lim_{x \rightarrow a} p(x) = p(a)$

Proof

$$\lim_{x \rightarrow a} x = a$$

$$\lim_{x \rightarrow a} x^i = a^i$$

$$\lim_{x \rightarrow a} a_i x^i = a_i a^i$$

$$\lim_{x \rightarrow a} \sum_{i=0}^n a_i x^i = \sum_{i=0}^n a_i a^i$$

 **Info – Limit of Rational Functions**

Let $f(x) = \frac{p(x)}{q(x)}$ when p, q be polynomial functions and $a \in \mathbb{R}$

1. If $q(a) \neq 0$ then $\lim_{x \rightarrow a} \frac{p(x)}{q(x)} = \frac{p(a)}{q(a)}$
2. If $\lim_{x \rightarrow a} q(a) = 0$ but then $\lim_{x \rightarrow a} p(x) \neq 0$ then $\lim_{x \rightarrow a} \frac{p(x)}{q(x)}$ is DNE.
If $x \rightarrow a, x < 0$, then the limit diverges to $-\infty$.
If $x \rightarrow a, x > 0$, then the limit diverges to ∞ .
3. Otherwise, $p(a) = 0 = q(a)$, so both $p(x)$ and $q(x)$ have $(x - a)$ as a factor. Divide it out and then repeat the process.

Examples:

$$1. \lim_{x \rightarrow -3} \frac{x^3 + 10x^2 + 13x - 24}{x^2 - 4x - 21}$$

$$\Rightarrow \stackrel{\left[\frac{0}{0} \right]}{=} \lim_{x \rightarrow -3} \frac{(x+3)(x-1)(x+8)}{(x+3)(x-7)} = \lim_{x \rightarrow -3} \frac{(x-1)(x+8)}{(x-7)} = \frac{(-3-1)(-3+8)}{(-3-7)} = \frac{-20}{-10} = 2$$

 **Info – Squeeze Theorem(Functions):**

If $g(x) \leq f(x) \leq h(x)$ be functions defined in an open interval I around a except possibly at a .

If $\forall a \in I \setminus \{a\}$ we have $g(x) \leq f(x) \leq h(x)$ and $\lim_{x \rightarrow a} g(x) = \lim_{x \rightarrow a} h(x) = L$, then $\lim_{x \rightarrow a} f(x) = L$

 **Tip – When to apply Squeeze Theorem**

1. Trigonometric functions with clear bounds and polynomial terms before
2. Exponential Functions with constants terms or by defining a certain interval

2. Evaluate $\lim_{x \rightarrow 0} x^2 \cos\left(\frac{1}{x}\right)$

$$-1 \leq \cos\left(\frac{1}{x}\right) \leq 1$$

$$-x^2 \leq x^2 \cos\left(\frac{1}{x}\right) \leq x^2$$

Notice that x^2 are polynomial function that is defined in $x \in \mathbb{R}$.

$$\lim_{x \rightarrow 0} -x^2 = \lim_{x \rightarrow 0} x^2 = 0$$

By Squeeze Theorem, $\lim_{x \rightarrow 0} x^2 \cos\left(\frac{1}{x}\right) = 0$

One Sided Limits and the Fundamental Trig Limit

1. We say that L is the **right side limit** of f at a , and write $\lim_{x \rightarrow a^+} f(x) = L$ if $\forall \varepsilon > 0, \exists \delta > 0$ s.t. if $|x - a| < \delta$ and $x > a$ then $|f(x) - L| < \varepsilon$
2. We say that L is the **left side limit** of f at a , and write $\lim_{x \rightarrow a^-} f(x) = L$ if $\forall \varepsilon > 0, \exists \delta > 0$ s.t. if $|x - a| < \delta$ and $x < a$ then $|f(x) - L| < \varepsilon$



Info – Theorem

$$\lim_{x \rightarrow a} f(x) = L \iff \lim_{x \rightarrow a^-} f(x) = \lim_{x \rightarrow a^+} f(x) = L$$

Example:

Show that $\lim_{x \rightarrow 0} \sin(x) = 0$, $\lim_{x \rightarrow 0} \cos(x) = 1$, and $\lim_{x \rightarrow 0} \tan(x) = 0$

1. $\lim_{x \rightarrow 0} \sin(x)$:

Construct a unit circle with a triangle that lies in the first quadrant and an arbitrary point, say $P(x, y)$. Then $P(x, y) = P(\cos(x), \sin(y))$. The area of the triangle can be represented as $\frac{1}{2} \sin(x)$.

Construct another unit circle and draw $P(x, y)$ at the same location as the previous triangle, however, construct an sector. The area of this new sector is $\frac{1}{2}x$.

Notice that the area bounded by the sector is bigger than the triangle.

We then have $0 \leq \frac{1}{2} \sin(x) \leq \frac{1}{2}x \implies 0 \leq \sin(x) \leq x$. Since $\lim_{x \rightarrow 0^+} 0 = \lim_{x \rightarrow 0^+} x = 0$, by Squeeze Theorem, $\lim_{x \rightarrow 0^+} \sin(x) = 0$

$\lim_{x \rightarrow 0^-} \sin(x) = 0$ can be achieved similarly to the prove of right side limit and will be omitted.

Thus $\lim_{x \rightarrow 0} \sin(x) = 0$

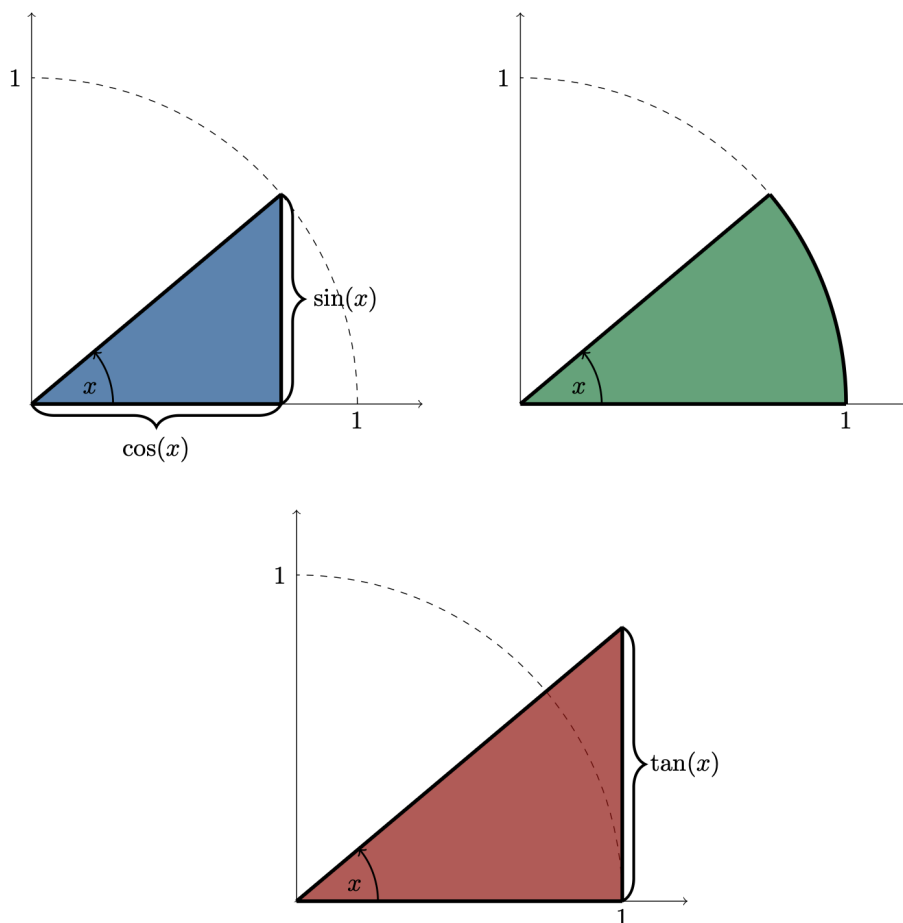
2. $\lim_{x \rightarrow 0} \cos(x) = 1$:

$$\lim_{x \rightarrow 0} \cos(x) = \lim_{x \rightarrow 0} \sqrt{1 - \sin^2(x)} = 1$$

3. $\lim_{x \rightarrow 0} \tan(x) = \lim_{x \rightarrow 0} \frac{\sin(x)}{\cos(x)} = 1$

⚠ Warning – The Fundamental Trig Limit:

$$\lim_{x \rightarrow 0} \frac{\sin(x)}{x} = 1$$



We have that $\frac{1}{2} \cos(x) \sin(x) \leq \frac{1}{2} x \leq \frac{1}{2} \tan(x) \implies \cos(x) \leq \frac{x}{\sin(x)} \leq \frac{1}{\cos(x)}$.

By Squeeze Theorem, $\lim_{x \rightarrow 0^+} \frac{\sin(x)}{x} = 1$.

Since $\sin(x)$ is an even function, then $\frac{\sin(-x)}{-x} = \frac{-\sin(x)}{-x} = \frac{\sin(x)}{x}$ so $\lim_{x \rightarrow 0^-} \frac{\sin(x)}{x} = 1$

$$\therefore \lim_{x \rightarrow 0} \frac{\sin(x)}{x} = 1$$

Examples:

- $\lim_{x \rightarrow 0} \frac{\tan(x)}{x} = \lim_{x \rightarrow 0} \frac{\sin(x)}{x} \cdot \frac{1}{\cos(x)} = \lim_{x \rightarrow 0} \frac{\sin(x)}{x} \cdot \lim_{x \rightarrow 0} \frac{1}{\cos(x)} = 1 \cdot 1 = 1$
- $\lim_{x \rightarrow 0} \frac{\sin(72x)}{\tan(9x)} = \lim_{x \rightarrow 0} \frac{\sin(72x)}{72x} \cdot \frac{9x}{\tan(9x)} \cdot 8 = \lim_{x \rightarrow 0} \frac{\sin(72x)}{72x} \cdot \lim_{x \rightarrow 0} \frac{9x}{\tan(9x)} \cdot 8 = 1 \cdot 1 \cdot 8$
- $\lim_{x \rightarrow 0} \frac{\sin(x^2-1)}{\sin(x-1)} = \lim_{x \rightarrow 0} \frac{\sin(x^2-1)}{\sin(x-1)} \cdot \frac{x^2-1}{x^2-1} \cdot \frac{x-1}{x-1} = \lim_{x \rightarrow 0} \frac{\sin(x^2-1)}{x^2-1} \cdot \lim_{x \rightarrow 0} \frac{x-1}{\sin(x-1)} \cdot \lim_{x \rightarrow 0} (x+1) = 1 \cdot 1 \cdot 1 = 1$

Horizontal Asymptotes and the Fundamental Log Limit

Info – Limit at $\pm\infty$

Let $L \in \mathbb{R}$.

We say that $\lim_{x \rightarrow \infty} f(x) = L$ if $\forall \varepsilon > 0, \exists N \in \mathbb{R}$ s.t. if $x > N$, then $|f(x) - L| < \varepsilon$.

Similarly, $\lim_{x \rightarrow -\infty} f(x) = L$ if $\forall \varepsilon > 0, \exists N \in \mathbb{R}$ s.t. if $x < -N$, then $|f(x) - L| < \varepsilon$.

Info – Horizontal Asymptotes

If $\lim_{x \rightarrow \infty} f(x) = L$ or $\lim_{x \rightarrow -\infty} f(x) = L$ for some $L \in \mathbb{R}$ then we say $y = L$ is a **Horizontal Asymptote** of f

Note: you can cross horizontal asymptotes multiple times

Info – Divergence of Limits

1. We say that $\lim_{x \rightarrow \infty} f(x) = \infty$ if, $\forall M > 0, \exists N \in \mathbb{R}$ s.t. if $x > N$ we have $f(x) > M$.
2. We say that $\lim_{x \rightarrow -\infty} f(x) = \infty$ if, $\forall M > 0, \exists N \in \mathbb{R}$ s.t. if $x < -N$ we have $f(x) > M$.
3. We say that $\lim_{x \rightarrow \infty} f(x) = -\infty$ if, $\forall M < 0, \exists N \in \mathbb{R}$ s.t. if $x > N$ we have $f(x) < M$.
4. We say that $\lim_{x \rightarrow -\infty} f(x) = -\infty$ if, $\forall M < 0, \exists N \in \mathbb{R}$ s.t. if $x < -N$ we have $f(x) < M$.

Info – Squeeze Theorem at $\pm\infty$

If $g(x) \leq f(x) \leq h(x) \forall x \geq N$ for some $N \in \mathbb{R}$, and if

$\lim_{x \rightarrow \infty} g(x) = L = \lim_{x \rightarrow \infty} h(x)$, then $\lim_{x \rightarrow \infty} f(x) = L$

Warning – The Fundamental Log Limit

$$\lim_{x \rightarrow \infty} \frac{\ln(x)}{x} = 0$$

Proof

$0 \leq \frac{\ln(x)}{x}$ true whenever $x \geq 1$. Since $x \rightarrow \infty$, assume $x \geq 1$.

$$\frac{\ln(x)}{x} = \frac{\ln(\sqrt{x} \cdot \sqrt{x})}{\sqrt{x} \cdot \sqrt{x}} = \frac{2 \ln(\sqrt{x})}{\sqrt{x} \cdot \sqrt{x}} = \frac{2}{\sqrt{x}} \cdot \frac{\ln(\sqrt{x})}{\sqrt{x}} \leq 1 \leq \frac{2}{\sqrt{x}} \text{ (since } \ln(z) \leq z, \forall z \text{ arbitrarily large)}$$

$$0 \leq \frac{\ln(x)}{x} \leq \frac{2}{\sqrt{x}}. \text{ By Squeeze Theorem } \lim_{x \rightarrow \infty} \frac{\ln(x)}{x} = 0$$

Examples:

1. Show that $\lim_{x \rightarrow \infty} \frac{\ln(x)}{x^p} = 0, \forall p > 0$

$$\lim_{x \rightarrow \infty} \frac{\ln(x)}{x^p} = \lim_{x \rightarrow \infty} \frac{\ln(x^p)}{x^p} \cdot \frac{1}{p} \quad \text{Let } u = x^p, x \rightarrow \infty, u \rightarrow \infty$$

$$\lim_{u \rightarrow \infty} \frac{\ln(u)}{u} \cdot \frac{1}{p} = 0 \cdot \frac{1}{p} = 0$$

2. Show that $\lim_{x \rightarrow \infty} \frac{\ln(x^p)}{x} = 0, \forall p > 0$

$$\lim_{x \rightarrow \infty} \frac{\ln(x^p)}{x} = \lim_{x \rightarrow \infty} p \cdot \lim_{x \rightarrow \infty} \frac{\ln(x)}{x} = p \cdot 0 = 0$$

3. Show that $\lim_{x \rightarrow \infty} \frac{x^p}{e^x} = 0, \forall p > 0$

$$\lim_{x \rightarrow \infty} \frac{x^p}{e^x} \quad \text{Let } x = \ln u \Leftrightarrow u = e^x, x \rightarrow \infty, u \rightarrow \infty$$

$$\lim_{u \rightarrow \infty} \frac{\ln(u)^p}{u} = \lim_{u \rightarrow \infty} \left(\frac{\ln(u)}{u^{\frac{1}{p}}} \right)^p = 0^p = 0$$

4. Show that $\lim_{x \rightarrow 0^+} \frac{x^p}{\ln(x)} = 0, \forall p > 0$

$$\lim_{x \rightarrow 0^+} \frac{x^p}{\ln(x)} \quad (\text{Let } u = \frac{1}{x})$$

$$\lim_{u \rightarrow \infty} \frac{1}{u^p} \cdot \ln\left(\frac{1}{u}\right) = 0$$

Info – Vertical Asymptotes

1. $\lim_{x \rightarrow a^+} f(x) = \infty$ if for every $m > 0, \exists \delta > 0$ s.t. if $a < x < a + \delta$ then $f(x) > m$
2. $\lim_{x \rightarrow a^-} f(x) = \infty$ if for every $m > 0, \exists \delta > 0$ s.t. if $a - \delta < x < a$ then $f(x) > m$
3. $\lim_{x \rightarrow a^+} f(x) = \lim_{x \rightarrow a^-} f(x) = \infty \implies \lim_{x \rightarrow a} f(x) = \infty$
4. If $\lim_{x \rightarrow a^\pm} f(x) = \pm\infty$ then there is a vertical asymptote at $x = a$

Info – Continuity

We say that a function f is **continuous** at a if f is defined at a and

1. $\lim_{x \rightarrow a} f(x) = f(a)$
2. For every $\varepsilon > 0, \exists \delta > 0$ s.t. if $|x - a| < \delta$, then $|f(x) - f(a)| < \varepsilon$
3. for every sequence $\{x_n\}$ with $x_n \rightarrow a$, we have $f(x_n) \rightarrow f(a)$
4. If f is not continuous at a , then it is called **discontinuous at a**

Example:

1. $f(x) = |x|$ is continuous at a

$$f(x) = \begin{cases} x & \text{if } x > 0 \\ -x & \text{if } x \leq 0 \end{cases}$$

$$\lim_{x \rightarrow 0^-} |x| = \lim_{x \rightarrow 0^-} -x = 0$$

$$\lim_{x \rightarrow 0^+} |x| = \lim_{x \rightarrow 0^+} x = 0$$

$$\text{Thus } \lim_{x \rightarrow 0} |x| = 0$$

Tip – Polynomials are continuous at all points

$$\lim_{x \rightarrow a} p(x) = p(a)$$

Info – Alternative way of Proving Continuity

$$\lim_{x \rightarrow a} f(x) = f(a) \equiv \lim_{h \rightarrow 0} f(a + h) = f(a)$$

Example:

1. Prove $\sin(x)$ is continuous at $x \in \mathbb{R}$

$$\sin(a + h) = \sin(a) \cos(h) + \sin(h) \cos(a)$$

$$\begin{aligned}
\lim_{x \rightarrow a} \sin(x) &= \lim_{h \rightarrow 0} \sin(a + h) \\
&= \lim_{h \rightarrow 0} \sin(a) \cdot \lim_{h \rightarrow 0} \cos(h) + \lim_{h \rightarrow 0} \sin(h) \cdot \lim_{h \rightarrow 0} \cos(a) \\
&= \sin(a) \cdot 1 + 0 \cdot \cos(a) = \sin(a)
\end{aligned}$$

2. Given that e^x is continuous at $x = 0$, prove that it is continuous on all of \mathbb{R}

$$\lim_{x \rightarrow a} e^x = \lim_{h \rightarrow 0} e^{a+h} = e^a \cdot 1 = \lim_{h \rightarrow 0} e^a$$

 **Tip – Continuity of Inverse**

Let $f(x)$ be invertible at $x = a$ with $f(a) = b$. Then $f^{-1}(y)$ is continuous at $y = b$

 **Info – Arithmetic Rules for Continuous Functions**

Let f, g be continuous at $x = a$.

1. For any constant $c \in \mathbb{R}$, $cf(x)$ is continuous at $x = a$
2. $f(x) \pm g(x)$ remain continuous
3. $f(x)g(x)$ remain continuous
4. If $g(x) \neq 0$, $\frac{f(x)}{g(x)}$ remain continuous

 **Info – Composition of Continuous Function**

If f is continuous at $x = a$, and g is continuous at $x = f(a)$, then $h = g \circ f$ is continuous at $x = a$

Proof:

Given f is continuous at a , then for any $\{x_n\}$, $x_n \rightarrow a$, $f(x_n) \rightarrow f(a)$. But g is continuous at $f(a)$, so for any $\{y_n\}$ with $y_n \rightarrow f(a)$, $g(y_n) \rightarrow g(f(a))$. Let $y_n = f(x_n)$. Then $g(f(x_n)) \rightarrow g(f(a))$ since x_n is arbitrary, $g \circ f$ is continuous at $x = a$

 **Tip – Continuity on Intervals**

1. We say that a function f is continuous on (a, b) if it is continuous at each $x \in (a, b)$
2. We say that a function f is continuous on $[a, b]$ if it is continuous on (a, b) and we have $\lim_{x \rightarrow a^-} f(x) = f(a)$ and $\lim_{x \rightarrow b^+} f(x) = f(b)$

Example:

Find the largest interval on which $f(x) = x^{\frac{1}{4}}$ is continuous.

For $(0, \infty)$ given $a \in (0, \infty)$, f is continuous at a^- because it is the inverse of x^4 , which is continuous at \mathbb{R} .

For $a = 0$, $\lim_{x \rightarrow 0^+} x^{\frac{1}{4}} = 0$, so f is continuous at 0 as well.

$\therefore f$ is continuous on $[0, \infty)$

Info – Types of Discontinuity

1. A discontinuity is a removable discontinuity if $\lim_{x \rightarrow a} f(x)$ exists but does not equal $f(a)$. All discontinuities not of this type are non-removable.
2. A discontinuity is a jump discontinuity if $\lim_{x \rightarrow a^-} f(x)$ and $\lim_{x \rightarrow a^+} f(x)$ exist but do not agree.
3. A discontinuity is infinite if either $\lim_{x \rightarrow a^-} f(x) = \pm\infty$ or $\lim_{x \rightarrow a^+} f(x) = \pm\infty$.
4. A discontinuity is oscillatory if $\lim_{x \rightarrow a} f(x)$ does not exist, but f is bounded and oscillates infinitely often near $x = a$.

Info – Intermediate Value Theorem (IVT)

If f is continuous on a closed interval $[a, b]$ and $\alpha \in \mathbb{R}$ is such that either $f(a) < \alpha < f(b)$ or $f(a) > \alpha > f(b)$, then $\exists c \in (a, b)$ s.t. $f(c) = \alpha$

Examples:

1. Show that $\sin(x)$ and $1 - x^2$ intersects on $(0, 1)$

Since $\sin(x)$ and $1 - x^2$ are continuous on \mathbb{R} therefore continuous on $[0, 1]$

For $x = 1$, $\sin(1) - 1 + (1)^2 = 1^2 - 1 > 0$

For $x = 0$, $\sin(0) - 1 + (0)^2 = -1 < 0$

$f(0) < 0 < f(1)$

By IVT, $\exists c \in (0, 1)$, $f(c) = 0$, meaning the given function intersect

2. Show that $x^3 + 3x^2 - x - 3$ has a root in the interval $(-5, -2)$

Since $x^3 + 3x^2 - x - 3$ is continuous on \mathbb{R} therefore continuous on $[-5, -2]$

For $x = -5$, $(-5)^3 + 3(-5)^2 - (-5) - 3 = -48 < 0$

For $x = -2$, $(-2)^3 + 3(-2)^2 - (-2) - 3 = 3 > 0$

$-48 < 0 < 3$

By IVT, $\exists c \in (-5, -2)$, $f(c) = 0$, meaning there is a point where the given function has a root

Info – Bisection Method

Let F be a continuous function.

To approximate a value c s.t. $F(c) = 0$ with an error of at most ε

1. We need to find a, b s.t. $F(a)$ and $F(b)$ have opposite signs
2. IVT gives that $c \in (a, b)$
3. Look at the mid-point $a + \frac{b-a}{2}$. Is $F(a + \frac{b-a}{2})$ positive or negative?
 $\left\{ \begin{array}{l} 1. \text{ If it has the same sign as } F(a), \text{ then it has the opposite sign with } F(b) \Rightarrow \text{IVT gives } c \in (a + \frac{b-a}{2}, b) \\ 2. \text{ If it has the opposite sign as } F(a), \text{ then it has the same sign with } F(b) \Rightarrow \text{IVT gives } c \in (a, a + \frac{b-a}{2}) \end{array} \right.$
4. Repeat Step 3 until $|b - a| < \varepsilon$

CHAPTER ENDS