

# Limits and Derivatives

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# Chapter 1

## Limits

### 1.1 Cases

#### 1.1.1 Case 1

Changing input values, output values remain the same  $\therefore$  The change in  $y$  with respect to changes  $x$  values is 0.  
This function is called a constant function

$$f(x) = k, \text{ for all input } x$$

#### 1.1.2 Case 2

Changing input values result in changing output values/ different output values.

$$f(x) = \text{not a constant function}$$

#### 1.1.3 Case 3

Changing input values result in a constant change in output values.

$$\Delta f(x) = \text{constant}$$

This function is called a linear function.

#### 1.1.4 Case 4

Changing input values result in a non constant change in output values

$$\Delta f(x) = \text{not constant}$$

### 1.1.5 Questions

#### Question 1

Find the derivative of  $f(x) = x^2$  at  $x = 1$

*Solution:*

$$\begin{aligned}\frac{d}{dx}f(x)_{x \rightarrow 1^-} &= 2 \\ \frac{d}{dx}f(x)_{x \rightarrow 1^+} &= 2 \\ \frac{d}{dx}x^2 &= 2\end{aligned}$$

#### Question 2

Investigate the existence or otherwise the derivatives if the following functions:

$$f(x) = \begin{cases} x^2, & \text{if } x \leq 2 \\ 1 + 2x & \text{if } x > 2 \end{cases} \text{ at } x = 2 \quad (1.1.1)$$

$$g(x) = |x| = \begin{cases} -x, & \text{if } x < 0 \\ x, & \text{if } x \geq 0 \end{cases} \text{ at } x = 0 \quad (1.1.2)$$

*Solution:* 1.1.1

$$\begin{aligned}\frac{d}{dx}f(x)_{x \rightarrow 2^-} &= 4 \\ \frac{d}{dx}f(x)_{x \rightarrow 2^+} &= \text{is not constant}\end{aligned}$$

*Solution:* 1.1.2

$$\begin{aligned}\frac{d}{dx}g(x)_{x \rightarrow 0^-} &= 1 \\ \frac{d}{dx}g(x)_{x \rightarrow 0^+} &= 1 \\ &= \frac{d}{dx}g(x) = 1\end{aligned}$$

# Chapter 2

## Derivatives

### 2.1 First Principle

- Slope or Gradient of a non-linear function
- Derivative =  $\frac{dy}{dx}$  = Instantaneous rate of change of a function
- Slope of a line =  $\frac{\Delta y}{\Delta x}$  = Average rate of change
- Leverage average rate of change to obtain the instantaneous rate of change = **First Principle**

$$\frac{dy}{dx} = \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h}$$

- The derivative is a function at a point and a number at another point

#### Definition 2.1.1: Secant

A line going through two points on a curve

#### 2.1.1 Questions

##### Question 3

Find the derivative of  $f(x) = x^2$  using first principle

*Solution:*

$$\begin{aligned} \frac{df}{dx} &= \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h} \\ &= \lim_{h \rightarrow 0} \frac{(x+h)^2 - x^2}{h} \\ &= \lim_{h \rightarrow 0} \frac{2hx + h^2}{h} \\ &= \lim_{h \rightarrow 0} (2x + h) \\ &= 2x \end{aligned}$$

**Question 4**

Find the derivative of  $f(x) = \frac{1}{x}$  using first principle

**Solution:**

$$\begin{aligned}
 \frac{df}{dx} &= \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h} \\
 \frac{df}{dx} &= \lim_{h \rightarrow 0} \left( \frac{1}{(x+h)} - \frac{1}{x} \right) \div h \\
 &\quad \frac{-h}{x^2 + hx} \div h \\
 &\quad \frac{-h}{x^2 + hx} \times \frac{1}{h} \\
 &\quad -\frac{1}{x^2 + hx} \\
 &\quad -\frac{1}{x^2 + 0x} \\
 \frac{df}{dx} &= \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h} = -\frac{1}{x^2}
 \end{aligned}$$

**Question 5**

Find the derivative of  $f(x) = \sqrt{x}$

**Solution:**

$$\begin{aligned}
 \frac{df}{dx} &= \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h} \\
 \frac{df}{dx} &= \lim_{h \rightarrow 0} = \frac{\sqrt{x+h} - \sqrt{x}}{h} \times \frac{\sqrt{x+h} + \sqrt{x}}{\sqrt{x+h} + \sqrt{x}} \\
 \frac{df}{dx} &= \lim_{h \rightarrow 0} = \frac{(\sqrt{x+h} - \sqrt{x}) - (\sqrt{x+h} + \sqrt{x})}{h(\sqrt{x+h} + \sqrt{x})} \\
 \frac{df}{dx} &= \lim_{h \rightarrow 0} = \frac{x+h-x}{h(\sqrt{x+h} + \sqrt{x})} \\
 \frac{df}{dx} &= \lim_{h \rightarrow 0} = \frac{h}{h(\sqrt{x+h} + \sqrt{x})} \\
 \frac{df}{dx} &= \lim_{h \rightarrow 0} = \frac{1}{\sqrt{x+h} + \sqrt{x}} \\
 &\quad \frac{1}{\sqrt{x+0} + \sqrt{x}} \\
 &\quad \frac{1}{2\sqrt{x}} \\
 \frac{df}{dx} &= \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h} = \frac{1}{2\sqrt{x}}
 \end{aligned}$$

## 2.2 Techniques of Differentiation

### 2.2.1 Power Rule

$$y = x^n$$

Where  $n$  is a real number

$$\frac{dy}{dx} = nx^{n-1}$$

#### Examples

**Example 2.2.1** ( $y = x^2$ ,  $n = 2$ )

$$\begin{aligned}\frac{dy}{dx} &= 2x^{2-1} \\ &= 2x^1 \\ &= 2x\end{aligned}$$

**Example 2.2.2** ( $y = \frac{1}{x^2}$ )

$$\begin{aligned}y &= x^{-2}, \quad n = -2 \\ y' &= -2x\end{aligned}$$

**Example 2.2.3** ( $y = \sqrt{x}$ )

$$\begin{aligned}y &= x^{\frac{1}{2}} \\ y' &= \frac{x^{-\frac{1}{2}}}{2} \\ y' &= \frac{1}{2\sqrt{x}}\end{aligned}$$

**Example 2.2.4** ( $y = \frac{1}{\sqrt{x}} + x^3 - 1$ )

$$\begin{aligned}y' &= x^{-\frac{1}{2}} + x^3 - 1 \\ y' &= -\frac{1}{2}x^{-\frac{3}{2}} + 3x^2\end{aligned}$$

**Example 2.2.5** ( $y = -x^{-8} + 3x^2$ )

$$y' = -8x^{-9} + 6x$$

## 2.3 Chain Rule

### Definition 2.3.1: Chain Function

A function that is composed of two or more functions, i.e,  $f[g]$

In the case where

$$y = (2x + 1)^2$$

The derivative is:

$$y' = 4(2x + 1)$$

### Examples

**Example 2.3.1** ( $y = (3x^2 + 2x)^5$ )

$$y = (5)(6x + 2)(3x^2 + 2x)^4$$

$$y = (30x + 10)(3x^2 + 2x)$$

$$y = 15x^9 - 3x^{12} + 5x - 46 \quad (2.3.1)$$

$$y = 2t^6 + 7t^{-6} \quad (2.3.2)$$

$$y = 8x^3 - \frac{1}{3x^5} + x - 23 \quad (2.3.3)$$

$$y = \sqrt{x} + 9\sqrt[3]{x^4} - \frac{2}{\sqrt[5]{x^2}} \quad (2.3.4)$$

$$y = \sqrt[3]{x^2}(2x - x^2) \quad (2.3.5)$$

$$y = \frac{2t^5 + t^2 - 5}{t^2} \quad (2.3.6)$$

$$y = 2x^3 + \frac{300}{x^3} + 4 \quad (2.3.7)$$

**Example 2.3.2** (2.3.1)

$$y' = 185x^8 - 36x^{11} + 5$$

**Example 2.3.3** (2.3.2)

$$y' = 12t^5 = 42t^{-7}$$

**Example 2.3.4** (2.3.3)

$$y = 8x^3 - \frac{1}{3x^5} + x - 23$$

$$y = 8x^3 - \frac{1}{3}x^{-5} + x - 23$$

$$y' = 24x^2 + \frac{5}{3}x^{-6} + 1$$



**Example 2.3.5** (2.3.4)

$$\begin{aligned}y &= \sqrt{x} + 9\sqrt[3]{7} - \frac{2}{\sqrt[5]{x^2}} \\y &= x^{\frac{1}{2}} + 9(x^7)^{\frac{1}{3}} - 2(x^2)^{-\frac{1}{5}} \\y &= x^{\frac{1}{2}} + 9x^{\frac{7}{3}} - 2x^{-\frac{2}{5}} \\y' &= \frac{1}{2}x^{-\frac{1}{2}} + 21x^{\frac{4}{3}} + \frac{4}{5}x^{-\frac{7}{5}} \\y' &= \frac{1}{2\sqrt{x}} + 21x^{\frac{4}{3}} + \frac{4}{5}x^{-\frac{7}{5}}\end{aligned}$$

**Example 2.3.6** (2.3.5)

$$\begin{aligned}y &= (x^2)^{\frac{1}{3}}(2x - x^2) \\y &= x^{\frac{2}{3}}(2x - x^2) \\y &= 2x^{\frac{5}{3}} - x^{\frac{8}{3}} \\y' &= \frac{10}{3}x^{\frac{2}{3}} - \frac{8}{3}x^{\frac{5}{3}}\end{aligned}$$

**Example 2.3.7** (2.3.6)

$$\begin{aligned}y &= 2t^3 + 1 - \frac{5}{t^2} \\y &= 2t^3 + 1 - 5t^{-2} \\y' &= 6t^2 + 10t^{-3}\end{aligned}$$

**Example 2.3.8** (2.3.7)

$$\begin{aligned}y &= 2x^3 + 300x^{-3} + 4 \\y' &= 6x^2 - 900x^{-4}\end{aligned}$$

## 2.4 Product Rule

Given  $y = u \times v$ , then the derivative is given by:

$$\frac{dy}{dx} = u' \times v + v' \times u$$

### Examples

**Example 2.4.1** ( $y = (x^2 + 1)(x^3 - x)$ )

$$\begin{aligned}y' &= (2x)(x^3 - x) + (x^2 + 1)(3x^2 - 1) \\y' &= 2x^4 - 2x^2 + 3x^4 + 2x^2 - 1 \\y' &= 5x^4 - 1\end{aligned}$$

**Example 2.4.2** ( $y = (6x^3 - x)(10 - 20x)$ )

$$\begin{aligned}y' &= (18x^2 - 1)(10 - 20x) + (-20)(6x^3 - x) \\y' &= 180x^2 - 10 - 360x^3 + 20x - 120x^3 + 20x \\y' &= -480x^3 + 180x^2 + 40x - 10\end{aligned}$$

### Questions

#### Question 6

$$y = (4t^2 - t)(t^3 - 8t^2 + 12)$$

**Solution:**

$$\begin{aligned}y' &= (8t - 1)(t^3 - 8t^2 + 12) + (3t^2 - 16t)(4t^2 - t) \\y' &= 8t^4 - 64t^3 + 96t - t^3 + 8t^2 - 12 + 12t^4 - 3t^3 - 64t^3 + 16t^2 \\y' &= 20t^4 - 132t^3 + 24t^2 + 96t - 12\end{aligned}$$

#### Question 7

$$y = (1 + \sqrt{x^3})(x^{-3} - 2\sqrt[3]{x})$$

**Solution:**

$$\begin{aligned}y &= (1 + (x^3)^{\frac{1}{2}})(x^{-3} - 2\sqrt[3]{x}) \\y &= (1 + x^{\frac{1}{2}})(x^{-3} - 2(x^{\frac{1}{3}})) \\y' &= (\frac{3}{2}x^{\frac{1}{2}})(x^{-3} - 2x^{\frac{1}{3}}) + (-3x^4 - \frac{2}{3}x^{-\frac{2}{3}} - \frac{2}{3}x^{\frac{5}{6}}) \\y' &= \frac{3}{2}x^{-\frac{5}{2}} - 3x^{\frac{5}{6}} - 3x^{-4} - 3x^{-\frac{5}{2}} - \frac{2}{3}x^{-\frac{2}{3}} - \frac{2}{3}x^{\frac{5}{6}} \\y' &= -\frac{11}{3}x^{\frac{5}{6}} - \frac{3}{2}x^{-\frac{5}{2}} - \frac{2}{3}x^{-\frac{2}{3}} - 3x^{-4}\end{aligned}$$

**Question 8**

$$y = (4 - t^2)(1 + 5t^2)$$

**Solution:**

$$y' = (-2t)(1 + 5t^2) + (10t)(4 - t^2)$$

$$y' = -2t - 10t^3 + 40t - 10t^3$$

$$y' = 20t^3 + 38t$$

**Question 9**

$$y = (x - \frac{2}{x^2})(7 - 2x^3)$$

**Solution:**

$$y = (x - 2x^{-2})(7 - 2x^3)$$

$$y' = (1 + 4x^{-3})(7 - 2x^3) + (-6x^2)(x - 2x^{-2})$$

$$y' = 7 - 2x^3 + 28x^{-3} - 8x^0 - 6x^3 + 12x^0$$

$$y' = 7 - 2x^3 + 28x^{-3} - 8 - 6x^3 + 12$$

$$y' = -8x^3 + \frac{28}{x^3} + 11$$

**Question 10**

$$y = (3 - x)(1 - 2x + x^2)$$

**Solution:**

$$y' = (-1)(1 - 2x + x^2) + (2x - 2)(3 - x)$$

$$y' = -1 + 2x - x^2 + 6x - 2x^2 - 6 + 2x$$

$$y' = -7 + 10x - 3x^2$$

## 2.5 Quotient Rule

Where  $y = \frac{f(x)}{g(x)}$ , the derivative is given by:

$$\frac{dy}{dx} = \frac{g(x) \times f'(x) - f(x) \times g'(x)}{(g(x))^2}$$

Or where  $\frac{u}{v}$

$$y' = \frac{v \times u' - u \times v'}{v^2}$$