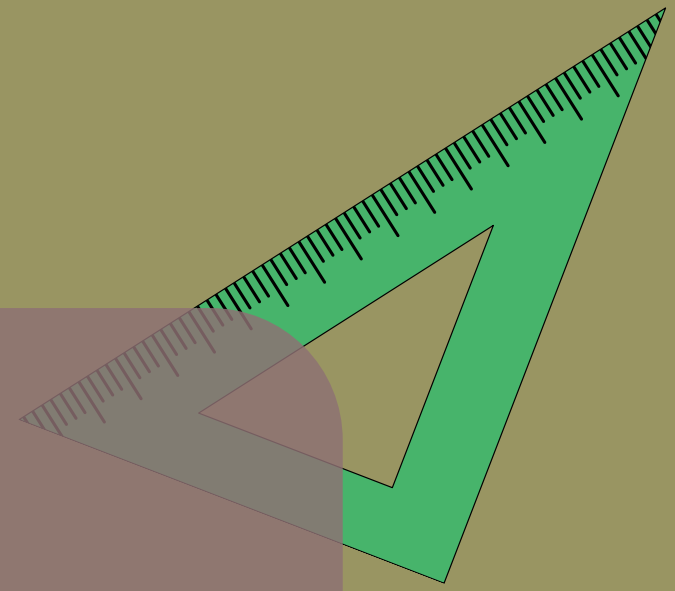
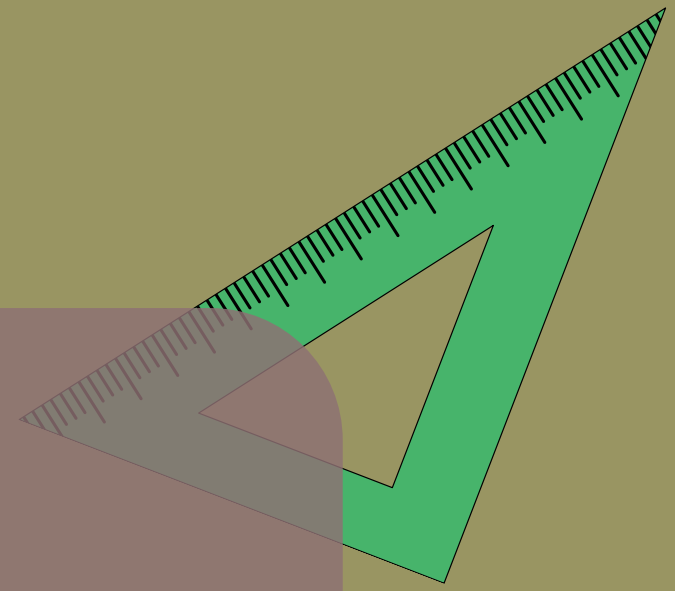




CALCULUS I DIFFERENTIATION





CALCULUS I DIFFERENTIATION

A i s h a h M a h a t
J a s e e n a J a f n i
N u r Q i s t i n a P u t r i M o h d F i t h r i



DISCLAIMER

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Author, Editor & Illustrator

Aishah Mahat

Jaseena Jafni

Nur Qistina Putri Mohd Fithri

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PREFACE

This e-book, Calculus 1 Differentiation, aimed to help students in Calculus subject. Targeted users for this module are students who take Calculus course. This e-book is divided into eight subtopics, which include The Definition of Derivatives, Techniques of Differentiation, Derivatives of Trigonometric, Exponential, and Logarithmic Functions, The Chain Rule, Equation of Tangent to the Curve, Second Derivative, Implicit Differentiation, and Linear Approximation. All eight subtopics above will be completed within 14 weeks in accordance with the planned lessons. Mathematical tips and formulas will be placed in accordance with the subtopics, whilst each calculus question will be displayed based on the syllabus covered during the lesson. At the end of each topic, targeted students should meet up with the lecturer to discuss the solution of Calculus problem. With the existence of this e-book, hopefully it will be beneficial and give positive impact on teaching and learning for students and lecturers as a whole.

BIOGRAPHY

Aishah Mahat is a lecturer at Universiti Teknologi MARA, Johor. Interests include optimisation and management mathematics. She graduated with second degree from Universiti Kebangsaan Malaysia in Mathematics.

Nur Qistina Putri Binti Mohd Fithri is a Diploma student in Civil Engineering who is currently pursuing her studies in engineering. She is a student who believes math, especially calculus, is best learned through doing. She focuses on understanding how calculus works when solving real engineering works.

Jaseena Binti Jafni is also a Diploma student in Civil Engineering. She is interested in making calculus easier to understand for others. She focuses on making a guide for others to understand calculus even more and believes that a clear insight into calculus can help future engineers with real-life engineering problems.

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FORMULA

RULES OF DIFFERENTIATION

1. Product Rule

$$\frac{d}{dx} [f(x)g(x)] = f(x)g'(x) + g(x)f'(x)$$

2. Quotient Rule

$$\frac{d}{dx} \left[\frac{f(x)}{g(x)} \right] = \frac{g(x)f'(x) - f(x)g'(x)}{[g(x)]^2}$$

3. Power Rule

$$\frac{d}{dx} [g(x)]^n = n[g(x)]^{n-1}g'(x)$$

LIST OF INTEGRALS

$$1. \quad \int (ax + b)^n dx = \begin{cases} \frac{(ax + b)^{n+1}}{a(n+1)} + C; & n \neq -1 \\ \frac{1}{a} \ln|ax + b| + C & n = -1 \end{cases}$$

$$2. \quad \int \frac{1}{x} dx = \ln|x| + C$$

$$3. \quad \int \sin ax dx = -\frac{1}{a} \cos ax + C$$

$$4. \quad \int \cos ax dx = \frac{1}{a} \sin ax + C$$

$$5. \quad \int \sec^2 ax dx = \frac{1}{a} \tan ax + C$$

$$6. \quad \int \csc^2 ax dx = -\frac{1}{a} \cot ax + C$$

FORMULA

THE SQUEEZING THEOREM

$$1. \quad \lim_{x \rightarrow 0} \frac{\sin x}{x} = 1$$

$$2. \quad \lim_{x \rightarrow 0} \frac{1 - \cos x}{x} = 0$$

DEFINITION OF DIFFERENTIATION

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

LINEAR APPROXIMATION

$$f(x) \approx f(x_0) + f'(x_0)(x - x_0)$$

THE SECOND FUNDAMENTAL THEOREM OF CALCULUS

$$\frac{d}{dx} \left[\int_a^{g(x)} f(t) dt \right] = f[g(x)]g'(x)$$

2.1 THE DEFINITION OF DERIVATIVE

- the derivative of $f(x)$ with respect to x is the function $f'(x)$.
- the derivative interpreted in two main ways:
 1. $f'(a)$ is the slope of the tangent line to the curve $y = f(x)$ at the point $(a, f(a))$.
 2. $f'(x)$ measures the instantaneous rate of change of y with respect to x .

FORMULA

$$f'(x) = \frac{f(x+h) - f(x)}{h}$$

EXAMPLE 1:

Determine $f'(x)$ if $f(x) = 2x + 3$ using the definition of differentiation.

- State the Definition of Differentiation

$$f'(x) = \frac{f(x+h) - f(x)}{h}$$

- Replace x with $(x + h)$ in the function $f(x) = 2x + 3$

$$f(x+h) = 2(x+h) + 3$$

$$f(x+h) = 2x + 2h + 3$$

- Substitute $f(x + h)$ and $f(x)$ into the limit definition

$$f'(x) = \lim_{h \rightarrow 0} \frac{(2x + 2h + 3) - (2x + 3)}{h}$$

- Simplify the Numerator

$$f'(x) = \lim_{h \rightarrow 0} \frac{2x + 2h + 3 - 2x - 3}{h}$$

$$f'(x) = \lim_{h \rightarrow 0} \frac{2h}{h}$$

- Evaluate the limit

$$f'(x) = 2$$

2.2 TECHNIQUES OF DIFFERENTIATION

CONSTANT FUNCTION

- Derivative of Constant Function

$$\frac{d}{dx} (c) = 0$$

POWER FUNCTION

- Power Rule

$$f(x) = x^n, \frac{d}{dx} (x^n) = nx^{n-1}$$

- Constant Multiple Rule

$$\frac{d}{dx} [c f(x)] = c \frac{d}{dx} f(x)$$

- The Sum Rule

$$\frac{d}{dx} [f(x) + g(x)] = \frac{d}{dx} f(x) + \frac{d}{dx} g(x)$$

- The Difference Rule

$$\frac{d}{dx} [f(x) - g(x)] = \frac{d}{dx} f(x) - \frac{d}{dx} g(x)$$

- The Product Rule

$$\frac{d}{dx} [f(x) g(x)] = uv' + vu' \text{ or } u \frac{dv}{dx} + v \frac{du}{dx}$$

- The Quotient Rule

$$\frac{d}{dx} \left[\frac{f(x)}{g(x)} \right] = \frac{vu' - uv'}{v^2} \text{ or } \frac{\left(\frac{v du}{dx} \right) - \left(u \frac{dv}{dx} \right)}{v^2}$$

THE DERIVATIVES OF STANDARD FUNCTIONS

$f(x)$	$f'(x)$
c	0
x^2	$2x$
$\sin x$	$\cos x$
$\cos x$	$-\sin x$
$\tan x$	$\sec^2 x$
$\sec x$	$\sec x \tan x$
$\ln x$	$1/x$
e^x	e^x

EXAMPLE 1:

Differentiate each of the following with respect to x .

$$\begin{aligned} \text{a) } f(x) &= 5 \\ f'(x) &= 0 \end{aligned}$$

$$\begin{aligned} \text{b) } y &= x \\ \frac{dy}{dx} &= 1 \end{aligned}$$

$$\begin{aligned} \text{c) } f(x) &= x^2 \\ f'(x) &= 2x \end{aligned}$$

$$\begin{aligned} \text{d) } y &= \sqrt{x} \\ y &= x^{1/2} \\ \frac{dy}{dx} &= \frac{1}{2} x^{-1/2} \\ &= \frac{1}{2\sqrt{x}} \end{aligned}$$

$$\begin{aligned} \text{e) } f(x) &= \frac{1}{x} \\ f'(x) &= -x^{-2} \\ &= -\frac{1}{x^2} \end{aligned}$$

EXAMPLE 2:

Differentiate each of the following with respect to x .

$$\text{a) } y = 3x^2 - 3x + 6$$

$$\frac{dy}{dx} = 6x - 3$$

$$\text{b) } f(x) = (2 - 3x)^2$$

$$\begin{aligned} &= (2 - 3x)(2 - 3x) \\ &= 4 - 6x - 6x + 9x^2 \\ &= 4 - 12x + 9x^2 \end{aligned}$$

$$f'(x) = -12 + 18x$$

EXAMPLE 3:

If $f(x) = (x^2 - 2)(4x^2 + x)$, find $f'(x)$

- identify and differentiate u and v

$$\begin{aligned} u &= x^2 - 2 & v &= 4x^2 + x \\ u' &= 2x & v' &= 8x + 1 \end{aligned}$$

- apply the product rule formula

$$\frac{d}{dx} (f(x)g(x)) = uv' + vu'$$

$$f'(x) = (x^2 - 2)(8x + 1) + (4x^2 + x)(2x)$$

- expand and simplify

$$f'(x) = 16x^3 + 3x^2 - 11x - 2$$

EXAMPLE 4:

If $y = \frac{3-2x}{x^2+4}$, find $\frac{dy}{dx}$

- identify and differentiate u and v

$$\begin{aligned} u &= 3-2x & v &= x^2+4 \\ u' &= -2 & v' &= 2x \end{aligned}$$

- apply the quotient rule

$$\frac{dy}{dx} = \frac{vu' - uv'}{v^2}$$

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

- expand and simplify the numerator

$$\frac{dy}{dx} = \frac{(-2x-8) - (6x-4x^2)}{(x^2+4)^2}$$

$$\frac{dy}{dx} = \frac{2x-6x-8}{(x^2+4)^2}$$

2.3 DERIVATIVES OF TRIGONOMETRIC, EXPONENTIAL & LOGARITHMIC FUNCTIONS

$f(x)$ or y	$f'(x)$ or $\frac{dy}{dx}$
$\sin (x)$	$\cos (x)$
$\cos (x)$	$-\sin (x)$
$\tan (x)$	$\sec ^2(x)$
$\cot (x)$	$-\operatorname{cosec}^2(x)$
$\sec (x)$	$\sec (x) \tan (x)$
$\operatorname{cosec}(x)$	$-\operatorname{cosec}(x) \cot (x)$
e^x	e^x
$\ln (x)$	$\frac{1}{x}$

EXAMPLE 1:

Find the derivative $\frac{dy}{dx}$ of the following functions.

a) $y = x^2 \cos x$

- identify and differentiate u and v .

$$u = x^2$$

$$v = \cos x$$

$$u' = 2x$$

$$v' = -\sin x$$

- apply the product rule.

$$\frac{d}{dx} [f(x)g(x)] = uv' + vu'$$

$$\frac{dy}{dx} = (x^2)(-\sin x) + (\cos x)(2x)$$

- simplify

$$\frac{dy}{dx} = -x^2 \sin x + 2x \cos x$$

EXAMPLE 2:

Find the derivative $\frac{dy}{dx}$ of the following functions.

a) $y = \frac{\ln x}{3x^2}$

- identify and differentiate u and v .

$$\begin{array}{ll} u = \ln x & v = 3x^2 \\ u' = \frac{1}{x} & v' = 6x \end{array}$$

- apply the quotient rule.

$$\frac{d}{dx} \left[\frac{f(x)}{g(x)} \right] = \frac{vu' - uv'}{v^2}$$

$$\frac{dy}{dx} = \frac{(3x^2) \left(\frac{1}{x}\right) - (\ln x)(6x)}{(3x^2)^2}$$

- simplify

$$\frac{dy}{dx} = \frac{1 - 2 \ln x}{3x^3}$$

2.4 THE CHAIN RULE

- The chain rule is a formula used to find the derivative of a composite function, which is a function nested inside another function (like an "outer" and "inner" layer).
- Essentially, it states that to differentiate $f(g(x))$, you take the derivative of the outer function while keeping the inner function the same, and then multiply it by the derivative of the inner function.

THE CHAIN RULE FORMULAS

- Lagrange's Notation (Function Notation):

$$\frac{d}{dx} [f(g(x))] = f'(g(x)) \cdot g'(x)$$

- Leibniz's Notation (Variable Notation):

If $y = f(u)$ and $u = g(x)$, then:

$$\frac{dy}{dx} = \frac{dy}{du} \cdot \frac{du}{dx}$$

EXAMPLE 1:

$$f(x) = (3x^2 + 5)^4$$

- Identify the outer function, $f(u)$ and inner function, $g(x)$

$$\text{let } u = 3x^2 + 5$$

$$f(u) = u^4$$

$$g(x) = 3x^2 + 5$$

- Differentiate each function

$$f'(u) = 4u^3$$

$$g'(x) = 6x$$

- Multiply the derivatives

$$F'(x) = 4(3x^2 + 5)^3 \cdot 6x$$

- Simplify

$$F'(x) = 24x(3x^2 + 5)^3$$



EXAMPLE 2:

$$f(x) = \sin(x^3)$$

- Identify the outer function, $f(u)$ and inner function, $g(x)$

$$\text{let } u = x^3$$

$$f(u) = \sin u$$

$$g(x) = x^3$$

- Differentiate each function

$$f'(u) = \cos u$$

$$g'(x) = 3x^2$$

- Multiply the derivatives

$$F'(x) = \cos(x^3) \cdot 3x^2$$

- Simplify

$$F'(x) = 3x^2 \cos(x^3)$$



EXAMPLE 3:

$$y = \sqrt{3x^3 - 9x}$$

- Identify the outer function, $f(u)$ and inner function, $g(x)$

$$y = (3x^3 - 9x)^{1/2}$$

$$\text{let } u = 3x^3 - 9x$$

$$y = u^{1/2}$$

- Differentiate each function

$$y' = \frac{1}{2} u^{-1/2}$$

$$u' = 9x^2 - 9$$

- Multiply the derivatives

$$\frac{dy}{dx} = \frac{1}{2} (3x^3 - 9x)^{-1/2} \cdot 9x^2 - 9$$

- Simplify

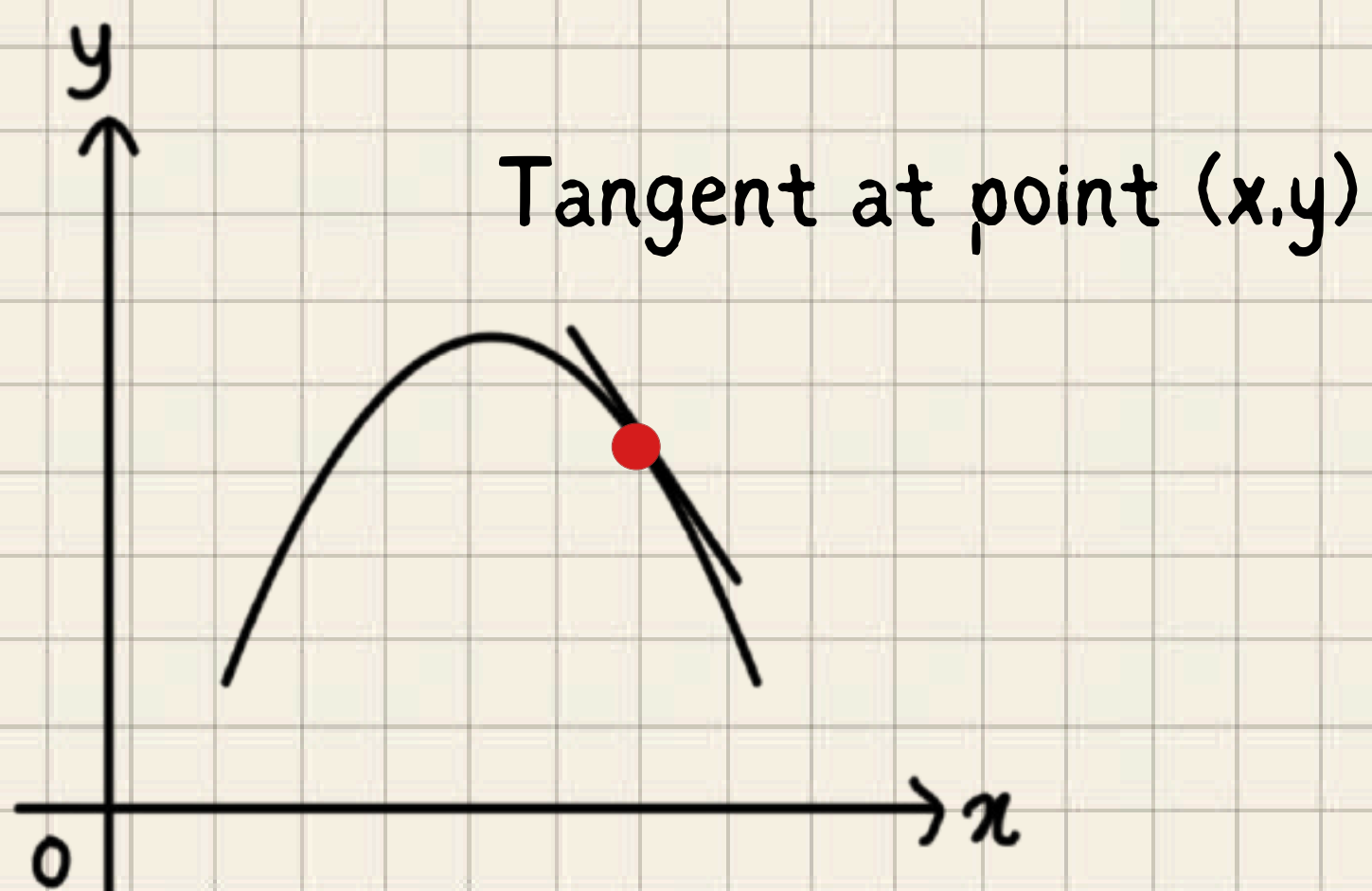
$$= \frac{9x^2 - 9}{2 \sqrt{3x^3 - 9x}}$$



2.5 EQUATION OF TANGENT TO A CURVE

WHAT IS TANGENT

- A tangent line to a curve at a specific point is a straight line that touches the curve at that exact point. It matches the direction and steepness of the curve at that single spot.
- In calculus, finding the equation of a tangent line bridges the gap between nonlinear curves and linear algebra. It tells us the instantaneous linear behavior of a function at a single moment.



2.5 EQUATION OF TANGENT TO A CURVE

STRAIGHT LINE EQUATION

- To write a straight line equation, only 2 pieces of information are required:
 1. A coordinate pair, (x,y) , where the line sits
 2. A slope, m , which is the steepness of the line
- In calculus, to find the gradient, m , is by finding the derivatives of the equation of the curve

$$m = f'(x_0)$$

- The formula for the straight line equation:

$$y - f(x_0) = f'(x_0)(x - x_0)$$

EXAMPLE :

$$f(x) = x^3 - 2x, \text{ where } x=2$$

- Find the y-coordinate (The point)

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

$$\begin{aligned} f(2) &= (2)^3 - 2(2) \\ &= 4 \end{aligned}$$

The coordinate of the point is (2,4)

- Find the derivatives of the function

$$f'(x) = 3x^2 - 2$$

- Calculate the specific slope by substituting the $x=2$ into $f'(x)$

$$\begin{aligned} m &= f'(2) = 3(2)^2 - 2 \\ &= 10 \\ m &= 10 \end{aligned}$$

- Substitute into the straight line equation

$$y - f(x_0) = f'(x_0)(x - x_0)$$

$$y - 4 = 10(x - 2)$$

$$y - 4 = 10x - 20$$

$$y = 10x - 16$$



2.6 SECOND DERIVATIVES

THE DERIVATIVE OF A DERIVATIVE

- If the first derivative represents the rate of change of a function, the second derivative represents the rate of change of the first derivative.
- In simple terms, it measures how fast the slope of a curve is changing.
- If the first derivative tells you whether you are moving up or down, the second derivative tells you how the curve is bending

HOW TO WRITE

- Lagrange's Notation (Prime Notation)

$$\text{First derivative} = f'(x)$$

$$\text{Second derivative} = f''(x)$$

- Leibniz's Notation

$$\text{First derivative} = \frac{dy}{dx}$$

$$\text{Second derivative} = \frac{d^2y}{dx^2}$$

2.6 SECOND DERIVATIVES

SECOND DERIVATIVE IN GRAPHS

- While the first derivative determines if a graph is increasing or decreasing, the second derivative determines the concavity (the direction of the bend) of the graph.

SIGN OF $f''(x)$	BEHAVIOUR OF SLOPE	SHAPE OF CURVE
POSITIVE (>0)	SLOPE INCREASES	CONCAVE UP
NEGATIVE (<0)	SLOPE DECREASES	CONCAVE DOWN
ZERO ($=0$), UNDEFINED	SLOPE STOPS BENDING	POSSIBLE INFLECTION POINT

INFLECTION POINT

- An inflection point occurs where a graph changes its concavity from concave up to concave down, or vice versa. To find potential inflection points in a problem, set $f''(x) = 0$ and solve for x

2.6 SECOND DERIVATIVES

REAL WORLD APPLICATIONS

- The easiest way to understand the physical meaning of the second derivative is through physics and motion:
 1. Displacement, $s(t)$: Position of the object
 2. Velocity, $v(t) / s'(t)$: Rate of change of displacement
 3. Acceleration, $a(t) / v'(t) / s''(t)$:
Rate of change of velocity
- If the velocity is positive but the acceleration is negative, the object is moving forward but slowing down. Graphically, this is an increasing function that is concave down.

EXAMPLE 1:

$$f(x) = x^4 - 5x^3 + 2x$$

- Find the first derivative

$$f'(x) = 4x^3 - 15x^2 + 2$$

- Differentiate the result

$$f''(x) = 12x^2 - 30x$$

EXAMPLE 2:

$$f(x) = \cos(3x)$$

- Find the first derivative

$$\begin{aligned} f'(x) &= -\sin(3x) \cdot 3 \\ &= -3 \sin(3x) \end{aligned}$$

- Differentiate the result

$$\begin{aligned} f''(x) &= -3 \cdot \cos(3x) \cdot 3 \\ &= -9 \cos(3x) \end{aligned}$$



2.7 IMPLICIT DIFFERENTIATIONS

- sometimes functions are given not in the form $y=f(x)$ but in a more complicated form.
- it is difficult to express y explicitly in terms of x .
- such functions are called implicit functions.
- $y = x^3 - 3x + 5 \rightarrow$ **explicit** because something is made clear and stated plainly
- $4x + y^3 = 2y + x^2 + 8 \rightarrow$ **implicit** because something is implied but not stated directly.

to differentiate a function y respect to x , we differentiate with respect to y and then multiply by $\frac{dy}{dx}$

EXAMPLE 1:

using implicit differentiations, solve $4x + y^3 = 2y + x^2 + 8$

- differentiate both sides with respect to x .

$$\frac{d}{dx}(4x) + \frac{d}{dx}(y^3) = \frac{d}{dx}(2y) + \frac{d}{dx}(x^2) + \frac{d}{dx}(8)$$

- evaluate the derivatives term by term.

$$4 + 3y^2 \frac{dy}{dx} = 2 \frac{dy}{dx} + 2x$$

- rearrange all $\frac{dy}{dx}$ terms on one side.

$$3y^2 \frac{dy}{dx} - 2 \frac{dy}{dx} = 2x - 4$$

$$(3y^2 - 2) \frac{dy}{dx} = 2x - 4$$

- solve for $\frac{dy}{dx}$

$$\frac{dy}{dx} = \frac{2x - 4}{3y^2 - 2}$$

2.8 LINEAR APPROXIMATIONS AND DIFFERENTIALS

ESTIMATING THE COMPLEX WITH THE SIMPLE

- Calculating complicated functions like $\ln(4.1)$ can be difficult without the help of a calculator.
- Linear approximation is a calculus technique that uses the tangent line at a known, easy-to-calculate point to estimate nearby values on a complex curve. Because a curve looks almost identical to its tangent line if you zoom in close enough, the line serves as a highly accurate proxy.
- Differentials provide the formal mathematical framework for this process. They isolate the estimated change in the vertical output (dy) based on a small change in the horizontal input (dx).

2.8 LINEAR APPROXIMATIONS AND DIFFERENTIALS

LINEAR APPROXIMATION (THE TANGENT LINE APPROXIMATION)

- If you have a function $f(x)$ that is differentiable at a specific, clean starting point $x = a$, you can construct its tangent line equation. When written as an estimation function, this is called the Linearization of f at a , denoted as $L(x)$.

THE LINEARIZATION FORMULA

- Derived directly from the point-slope formula, the template for linear approximation is:

$$L(x) = f(a) + f'(a)(x-a)$$

- For values of x that are very close to a , the function value is approximately equal to the linearization value: $f(x) \approx L(x)$.

EXAMPLE 1:

$$\sqrt{9.2}$$

- Define the function

$$\text{let } x = 9.2$$

$$f(x) = \sqrt{x}$$

- Choose a center point (closest whole number to x)

$$9.2 \rightarrow 9$$

$$a = 9$$

- Evaluate function, $f(a)$

$$f(9) = \sqrt{9} = 3$$

- Find the derivative and evaluate it to a

$$f'(x) = \frac{1}{2\sqrt{x}}$$

$$f'(9) = \frac{1}{2\sqrt{9}}$$



EXAMPLE 1:

- Build the linearization equation

$$\begin{aligned} L(x) &= f(9) + f'(9)(x - 9) \\ &= 3 + \frac{1}{6}(x - 9) \end{aligned}$$

- Substitute $x=9.2$ to approximate

$$f(9.2) \approx L(9.2) = 3 + \frac{1}{6}(9.2 - 9)$$

$$f(9.2) \approx 3.0333$$



2.8 LINEAR APPROXIMATIONS AND DIFFERENTIALS

DIFFERENTIALS

- While linear approximation looks at the new total value along the tangent line, differentials isolate the amount of change along the tangent line.

DEFINITION AND FORMULA

- Let $y = f(x)$ be a differentiable function.
- We define dx the differential of x to be an independent variable representing a small change in x (equivalent to Δx)
- We define dy (the differential of y) to be the dependent variable representing the estimated change in y along the tangent line.

$$dy = f'(x)dx$$

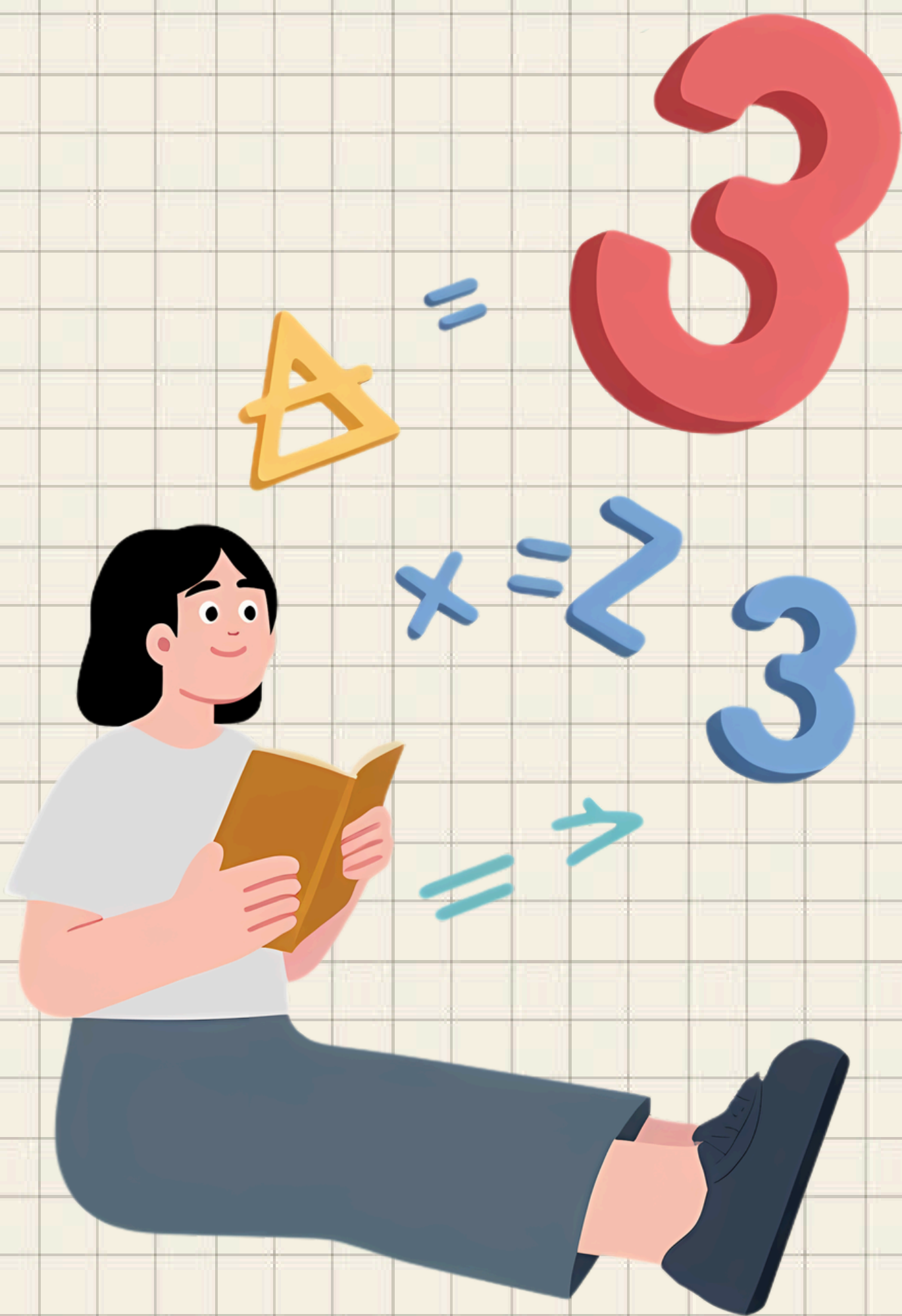
2.9 LINEAR APPROXIMATIONS AND DIFFERENTIALS

THE CONCEPT OF MATRIX: Δy Vs dy

TERM	SYMBOL	MEANING	HOW TO CALCULATE
ACTUAL CHANGE IN X	Δx	THE PHYSICAL CHANGE IN THE INPUT	$\Delta x = x_1 - x_0$
DIFFERENTIAL OF X	dx	EQUAL BY DEFINITION TO Δx	$dx = \Delta x$
ACTUAL CHANGE IN Y	Δy	THE TRUE VERTICAL RISE ON THE CURVE	$\Delta y = f(x - \Delta x) - f(x)$
DIFFERENTIAL OF Y	dy	THE ESTIMATED VERTICAL RISE ON THE TANGENT LINE	$dy = f'(x)dx$

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$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$V = \frac{4}{3} \pi r^3$$

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