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VCE Mathematical Methods ½
Polynomials [1.5]
Workbook

Outline:

Learning Objectives:

- ☐ **MM12 [1.5.1]** - Identify the properties of polynomials and solve long division.
- ☐ **MM12 [1.5.2]** - Apply remainder and factor theorem to find remainders and factors.
- ☐ **MM12 [1.5.3]** - Find factored form of polynomials.
- ☐ **MM12 [1.5.4]** - Graph factored and unfactored polynomials.

Section A: Algebra of Polynomial Functions

Sub-Section: Terminologies of Polynomials

Degree of Polynomial Functions

Degree = Highest Power of the Polynomial

Question 1 (5s)

State the degree of each polynomial.

a. $x^3 - 4x^2 + 5x + 6$

3

b. $3x + 5x^2 - x^7$

7

c. A Quadratic.

2

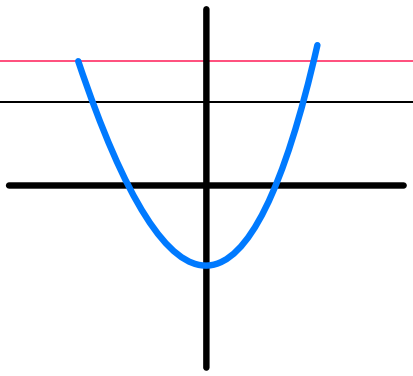
Roots of Polynomial Functions

$$Roots = x\text{-}intercept$$

Discussion: Can a quadratic have more than 2 roots? Hence, can there be more roots than the degree?

Degree = Max-ints / Roots of the polynomial

$f(x) = ax^2+bx+c$



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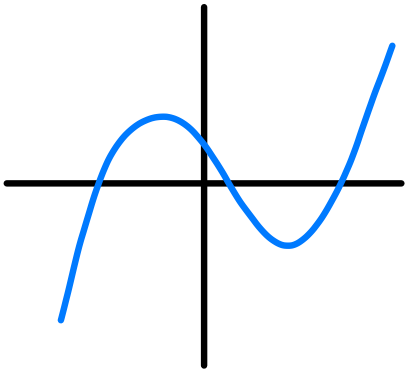
$g(x) = ax^3+bx^2+cx+d$



Question 2 5s

Find the roots of the following polynomial:

$$(x-1)^2(x+3)^4$$

$\therefore x = 1, -3$

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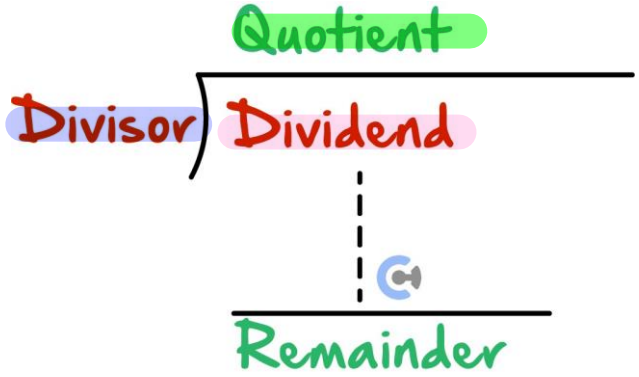
Sub-Section: Long Division

Polynomial Long Division

- Division of polynomials:



$$\frac{Dividend}{Divisor} = Quotient + \frac{Remainder}{Divisor}$$

Question 3 Walkthrough.

Simplify the following using polynomial long division.

$$\frac{3x^2 + 10x + 20}{2x + 4}$$

$$\begin{array}{r} \frac{3}{2}x + 2 \\ (2x+4)\overline{)\,3x^2+10x+20} \\ -(3x^2+6x) \\ \hline 4x+20 \\ -(4x+8) \\ \hline 12 \end{array}$$

$$\Rightarrow \frac{3}{2}x + 2 + \frac{12}{2x+4}$$

$$= \frac{3}{2}x + 2 + \frac{6}{x+2}$$

TIP: Always focus on the highest degree term first.

Your turn!

Question 4 (45s)

Simplify the following using polynomial long division.

$$\frac{x^2 - 3x + 5}{x - 1}$$

$1 \;|\; 1 \;\; -3 \;\; 5$

$\downarrow \;\; 1 \;\; -2$

$1 \;\; -2 \;\; 3$

$x \;\; c \;\; R$ "Remainder"

"Constant"

$= x - 2 \;\; R = 3$ //

$x-1 \;\overline{)\; x^2 - 3x + 5}$

$x - 2$

$-(x^2 - x)$

$-2x + 5$

$-(-2x + 2)$

3

$= x - 2 + \frac{3}{x-1}$

Now, a slightly more difficult example!

Question 5 (45s)

Simplify the following using polynomial long division.

$$\frac{x^3 + x^2 + 2}{x - 3}$$

$3 \;|\; 1 \;\; 1 \;\; 0 \;\; 2$

$\quad\quad 3 \;\; 12 \;\; 36$

$1 \;\; 4 \;\; 12 \;\; 38$

$= x^2 + 4x + 12 + \frac{38}{x-3}$

$x-3 \;\overline{)\; x^3 + x^2 + 2}$

$x^2 + 4x + 12$

$-(x^3 - 3x^2)$

$4x^2 + 2$

$-(4x^2 - 12x)$

$12x + 2$

$-(12x - 36)$

38

TIP: Always remember to fill in any missing powers of x in the numerator or denominator with "placeholders" that have a coefficient of 0.

Question 6 Extension. 45s

Simplify the following using polynomial long division.

$$\frac{x^4 + 4x^3 + 3x^2 - 2x + 3}{x + 3}$$

$$x+3 \overline{)\, x^4+4x^3+3x^2-2x+3}$$

$$x^3 + x^2 - 2$$

$$-(x^4 + 3x^3)$$

$$x^3 + 3x^2$$

$$-(x^3 + 3x^2)$$

$$0 - 2x + 3$$

$$-(-2x - 6)$$

$$9$$

$$-3 \overline{)\, 1 \quad 4 \quad 3 \quad -2 \quad 3}$$

$$-3 \quad -3 \quad 0 \quad 6$$

$$1 \quad 1 \quad 0 \quad -2 \quad 9$$

$$\Rightarrow x^3 + x^2 - 2 + \frac{9}{x+3}$$

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Sub-Section: Remainder Theorem

How can we find the remainder without long division?

Exploration: Derivation of the Remainder Theorem

- Consider $\frac{f(x)}{g(x)}$.

$$\frac{f(x)}{g(x)} = q(x) + \frac{R}{g(x)}, \text{ where } R = \text{Remainder}$$

$$g(x) \overline{)\, f(x)} \quad q(x)$$
$$-(q(x)g(x))$$
$$R$$

$$f(x) - q(x)g(x) = R$$

- Let's multiply everything by $g(x)$.

$$f(x) = q(x) \cdot g(x) + R$$

- Remember, we are trying to find the remainder R before we do long division.

  What functions do we already have before long division?

$$f(x) = q(x) \cdot g(x) + R$$

$q(x) = 0$

$g(x) = 0$

- How can we get $f(x)$ to equal to the remainder R?
  - We can substitute a value of x such that, the divisor $(g(x))$ is equal to 0.

$$f(\alpha) = q(\alpha) \cdot g(\alpha) + R$$

$$f(\alpha) = R$$

$g(x) = x - a$

$g(x) = 0$

$\therefore x = a$

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Remainder Theorem

- **Definition**: Finds the remainder of long division without the need of long division.

$$\textit{when } P(x) \textit{ is divided by } (x-\alpha), \textit{the remainder is } P(\alpha)$$

- **Steps:**
  1. Find x values which makes the divisor equal to 0.
  2. Substitute it into the dividend function.

Discussion: How do we find the remainder of $f(x) \div (x-2)$?

$\frac{f(x)}{x-2}$ → $x-2=0$, $x=2$ → $R=f(2)$

Discussion: How do we find the remainder of $f(x) \div (2x+1)$?

$\frac{f(x)}{2x+1}$ → $2x+1=0$, $x=-\frac{1}{2}$ → $R=f\left(-\frac{1}{2}\right)$

Question 7 Walkthrough.

Find the remainder of the division, $\frac{f(x)}{g(x)}$, where, $f(x)=x^3+x^2-2x+5$ and $g(x)=x+1$.

$g(x)=0$, $x=-1$ → $R=f(-1)=-1+1+2+5=7$

Your turn!

Active Recall: Remainder Theorem

1. Find x values which makes the denominator / divisor equal to 0.
2. Substitute it into the dividend / numerator function.

Question 8 (30s)

Find the remainder of the division, $\frac{f(x)}{g(x)}$, where, $f(x) = x^3 - 2x^2 + 3x + 1$ and $g(x) = 2x + 4$.

Let $g(x) = 0$:

$\therefore x = -2$

$R = f(-2)$

$= -8 - 8 - 6 + 1$

$= -21$ //

Question 9 Extension. (45s)

For the polynomial $f(x) = 3x^3 - 2x^2 + (7 - 2a)x + 1$, we get a remainder of 14 when $f(x)$ is divided by $g(x) = x - 1$. Find the value of a.

Let $g(x) = 0$:

$\therefore x = 1$

$R = f(1) = 14$

$= 3 - 2 + 7 - 2a + 1$

$= 9 - 2a = 14$

$\therefore -2a = 5$

$\therefore a = -\frac{5}{2}$

Sub-Section: Factor Theorem

Discussion: What division could $f(2)$ be the remainder of?

$\frac{f(x)}{x-2}$, $\frac{f(x)}{2x-4}$ .....

Discussion: Hence, what does it mean when $f(2) = 0$?

$\hookrightarrow R = 0$

$\therefore (x-2)$ is a factor

2 is a root (x-int)

This is called the "Factor theorem"

Factor Theorem

- For every x-intercept, there is a factor:

$$if\ P(\alpha) = 0\ then, (x - \alpha)\ is\ a\ factor\ of\ P(x)$$

Remainder $\frac{P(x)}{x+4}$? $\Rightarrow P(-4)$

Question 10 Walkthrough.

$R = 0$

Determine if $x + 4$ is a factor of $P(x) = 3x^3 + 8x^2 - 20x - 16$.

$P(-4) = 0$?

$P(-4) = 3(-64) + 8(16) + 80 - 16$

$= -192 + 128 + 80 - 16$

$= 0$

$\therefore (x+4)$ is a factor of $P(x)$

Your turn!

Question 11 (30s)

Determine if $x + 2$ is a factor of $P(x) = 2x^3 - 7x^2 + 7x - 2$.

$P(-2) = 0$?

Let $x+2 = 0$:

$\therefore x = -2$

$R = P(-2) = 2(-8) - 7(4) - 14 - 2$

$= -16 - 28 - 14 - 2$

$= -60$

$\therefore (x+2)$ ISN'T a factor of $P(x)$

Question 12 Extension. (1 min)

Determine if $x - \frac{3}{2}$ is a factor of $P(x) = 6x^3 - x^2 - 20x + 12$.

.

$x - \frac{3}{2} = 0$

$\therefore x = \frac{3}{2}$

Remainder when divided by $x - \frac{3}{2}$ is given by:

$R = P(\frac{3}{2}) = \cancel{6}^{3}(\frac{27}{\cancel{8}_{4}}) - (\frac{9}{4}) - 30 + 12$

$= \frac{81}{4} - \frac{9}{4} - 18$

$= \frac{72}{4} - \frac{72}{4} = 0$

$\therefore (x - \frac{3}{2})$ is a factor of $P(x)$ as $R = P(\frac{3}{2}) = 0$. //

Sub-Section: Factorising Polynomials

Factorising Polynomials

- The steps are:
  - Find a single root by trial and error.

    (Factor Theorem: Substitute into the function and see if we get zero.)
  - Use long division to find the quadratic factor.
  - Factorise the quadratic.

Question 13 Walkthrough.

Find all the roots of $f(x) = x^3 + 3x^2 - 6x - 8$.

1. Finding a Single Root (T&E):

Sub $x=1$:

$f(1) = 1+3-6-8 = -10$

Sub $x=2$:

$f(2) = 8+12-12-8 = 0$

$\therefore (x-2)$ is a factor

2. Long Division:

$$(x-2)\overline{)\,x^3+3x^2-6x-8}$$

x^2+5x+4

$-(x^3-2x^2)$

$5x^2-6x$

$-(5x^2-10x)$

$4x-8$

$-(4x-8)$

0

NOTE: When the question asks for all roots, you cannot just factorise and end it there!

3. Factorise:

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

$= (x-2)(x+4)(x+1)$

$\therefore x = 2, -4, -1$

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Your turn!

Question 14 1min 30s

Find all the roots of $f(x) = x^3 + 12x^2 + 17x - 90$.

1. Finding a Single Root (T&E):

Sub x=1:

$f(1) = 1+12+17-90 = -60$

Sub x=2:

$f(2) = 8+48+34-90 = 0$

∴ $(x-2)$ is a factor

2. Synthetic Division:

2	1	12	17	-90
		2	28	90
	1	14	45	0

3. Factorise:

$= (x-2)(x^2+14x+45)$

$= (x-2)(x+9)(x+5)$

∴ $x = 2, -9, -5$

Question 15 1min 30s

Find all the roots of $f(x) = -2x^3 - 13x^2 - 5x + 6$.

1. Finding a Single Root (T&E):

Sub x=1:

$f(1) = -2-13-5+6 = -14$

Sub x=-1:

$f(-1) = 2-13+5+6 = 0$

∴ $(x+1)$ is a factor

2. Synthetic Division:

-1	-2	-13	-5	6
		2	11	-6
	-2	-11	6	0

3. Factorise:

$= (x+1)(-2x^2-11x+6)$

$= (x+1)(-2x+1)(x+6)$

∴ $x = -1, \frac{1}{2}, -6$

~~Question 16~~

Find all the roots of $f(x) = 6x^3 - 27x^2 + 21x + 18$.

1. Finding a Single Root (T&E):

Sub x= :

f( )=

Sub x= 2:

f( )=

∴ ( ) is a factor

2. Long Division:

( ) $6x^3-27x^2+21x+18$

-( )

-( )

-( )

0

3. Factorise:

= ( )( )

= ( )( )( )

= ( )( )( )

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Sub-Section: Rational Root Theorem

Discussion: Consider $(2x-1)(3x-1)(6x-1)$. What are the roots and could we have gotten that from trial and error?

$x = \frac{1}{2}, \frac{1}{3}, \frac{1}{6}$

So, what should we do?

Rational Root Theorem

- Rational Root Theorem **narrows down** the possible roots.

$$\text{Potential root} = \pm \frac{\text{Factors of constant term } a_0}{\text{Factors of leading coefficient } a_n}$$

- If the roots are rational numbers, the roots can only be $\pm \frac{\text{factors of constant term } a_0}{\text{factors of leading coefficient } a_n}$.

Question 17 Walkthrough.

Find all the roots of $f(x) = 6x^3 + 13x^2 - 14x + 3$.

1. Finding a Single Root (RRT):

$RRT = \pm \frac{\{1,3\}}{\{1,2,3,6\}} = \pm\{1, \frac{1}{2}, \frac{1}{3}, \frac{1}{6}, \frac{3}{2}\}$

Sub $x = \frac{1}{2}$:

$f(\frac{1}{2}) = 6(\frac{1}{2})^3 + 13(\frac{1}{2})^2 - 14(\frac{1}{2}) + 3$

$= \frac{6}{8} + \frac{13}{4} - 7 + 3$

$= \frac{16}{8} - 4 = 0$

$\therefore (2x-1)$ is a factor

2. Long Division:

$$(2x-1)\overline{)6x^3+13x^2-14x+3}$$

$3x^2 + 8x - 3$

$-(6x^3 - 3x^2)$

$16x^2 - 14x$

$-(16x^2 - 8x)$

$-6x + 3$

$-(-6x + 3)$

0

3. Factorise:

$= (2x-1)(3x^2+8x-3)$

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

4. Find Root:

$\therefore x = \frac{1}{2}, \frac{1}{3}, -3$

NOTE: All the roots are part of the suggestion given by the rational root theorem.

Question 18

Find all the roots of $f(x) = 2x^3 - x^2 - 22x - 24$.

1. Finding a Single Root (RRT):

$RRT = \pm \frac{\{1,2,3,4,6,8,12,24\}}{\{1,2\}} = \pm\{1,2,3,4,6,8,12,24,\frac{1}{2},\frac{3}{2}\}$

Sub $x=4$:

$f(4) = 2(4)^3 - (4)^2 - 22(4) - 24$

$= 128 - 16 - 88 - 24$

$= 0$

$\therefore (x-4)$ is a factor

2. Synthetic Division:

4	2	-1	-22	-24
		8	28	24
	2	7	6	0

3. Factorise:

$= (x-4)(2x^2+7x+6)$

$= (x-4)(2x+3)(x+2)$

4. Find Root:

$\therefore x = 4, -\frac{3}{2}, -2$

Discussion: Why is rational root theorem called a rational root theorem?

→ rational no. is a no. that can be written as a fraction (of integers)

Factor: $(x-\sqrt{3})$

Roots: $\sqrt{3} \Rightarrow$ Irrational

π

ONLY finds RATIONAL ROOTS!

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Question 19 Extension.

Find all the roots of $f(x) = 6x^3 + 19x^2 - 24x - 16$.

1. Finding a Single Root (RRT):

$RRT = \pm \frac{\{1,2,4,8,16\}}{\{1,2,3,6\}}$

$= \pm\{1, 2, 4, 8, 16, \frac{1}{2}, \frac{1}{3}, \frac{2}{3}, \frac{4}{3}, \frac{8}{3}, \frac{16}{3}, \frac{1}{6}\}$

Sub $x=-4$:

$f(-4) = 6(-4)^3 + 19(-4)^2 - 24(-4) - 16$

$= 6(-64) + 19(16) + 96 - 16$

$= -384 + 304 + 80 = 0$

$\therefore (x+4)$ is a factor

2. Synthetic Division:

$-4 \mid 6 \quad 19 \quad -24 \quad -16$

$\quad\quad -24 \quad 20 \quad 16$

$6 \quad -5 \quad -4 \quad 0$

3. Factorise:

$= (x+4)(6x^2 - 5x - 4)$

$= (x+4)(3x-4)(2x+1)$

4. Find Root:

$\therefore x = -4, \frac{4}{3}, \frac{-1}{2}$

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Sub-Section: Sum and Difference of Cubes

Sum and Difference of Cubes

$$a^3 + b^3 = (a + b)(a^2 - ab + b^2)$$

$$a^3 - b^3 = (a - b)(a^2 + ab + b^2)$$

Question 20 Walkthrough.

Factorise the following polynomial as much as possible.

$$x^3 + 125$$

$\sqrt[3]{x^3}$ $\sqrt[3]{125}$

x 5

$$= (x+5)(x^2-5x+25)$$

Question 21

Factorise the following polynomial as much as possible.

$$8x^3 - 216$$

$$= 8(x^3 - 27)$$

$$= 8(x-3)(x^2+3x+9)$$

Question 22 Extension.

Factorise the following polynomial as much as possible.

$$32x^3 - 256$$

$= 32(x^3 - 8)$

$= 32(x-2)(x^2+2x+4)$.

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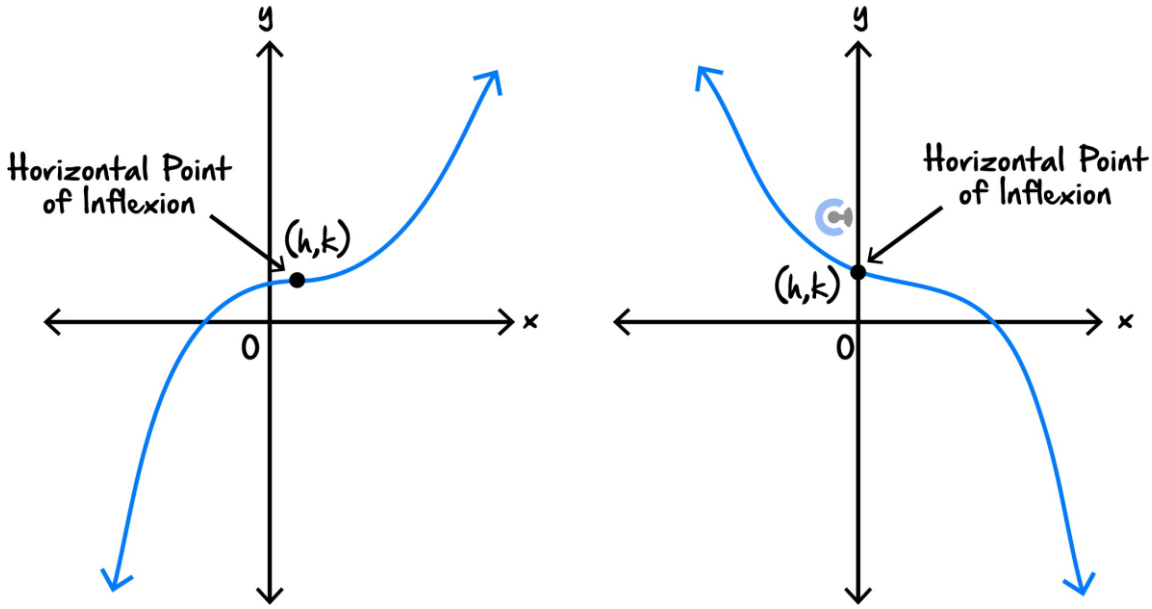
Section B: Graphs of a Polynomial

Sub-Section: Graphing Polynomials in the Form of $a(x-h)^n+k$

Graphs of $a(x-h)^n+k$, where n is an Odd Positive Integer

- All graphs look like a "cubic".



- The point (h,k) gives us the stationary point of inflection.
- n cannot be 1 for this shape to occur!

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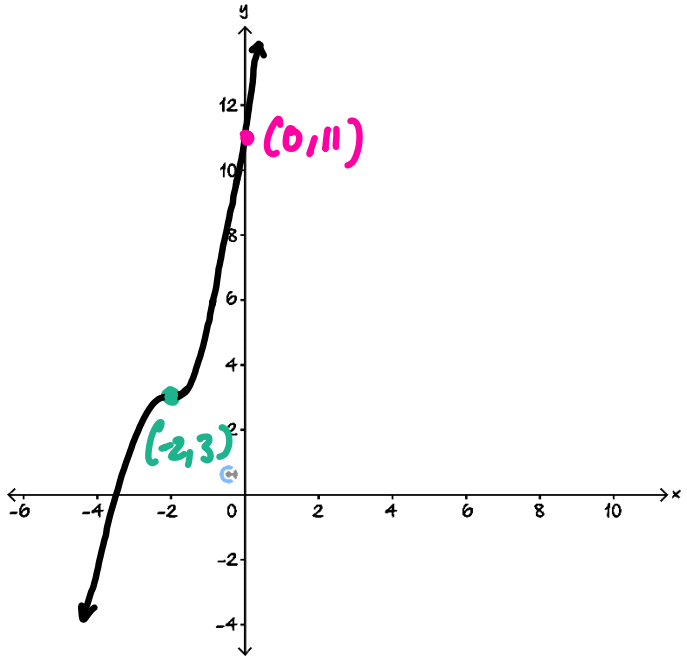
Question 23 Walkthrough.

POI : $(-2, 3)$

Y-int : $y = (2)^3 + 3 = 11$

Sketch the graph of $y = (x + 2)^3 + 3$ on the axes below.

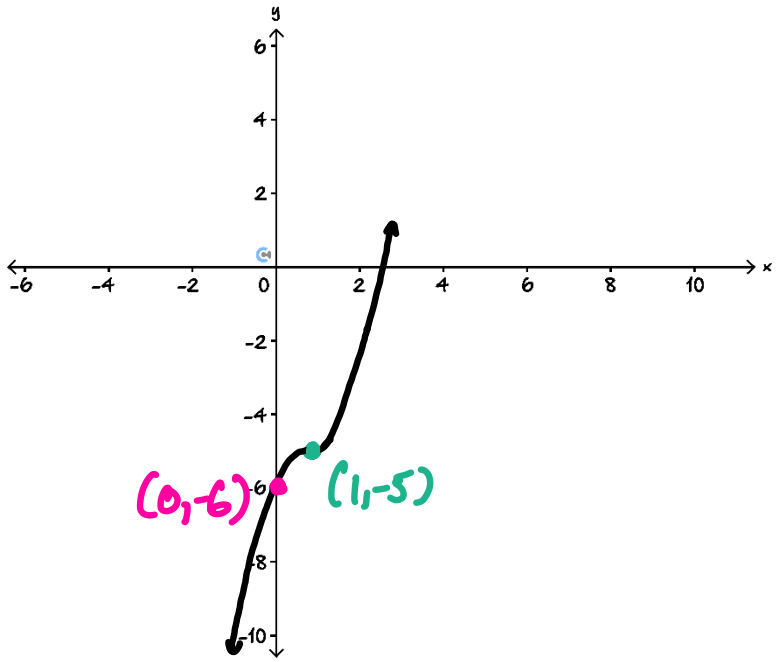


Question 24

POI : $(1, -5)$

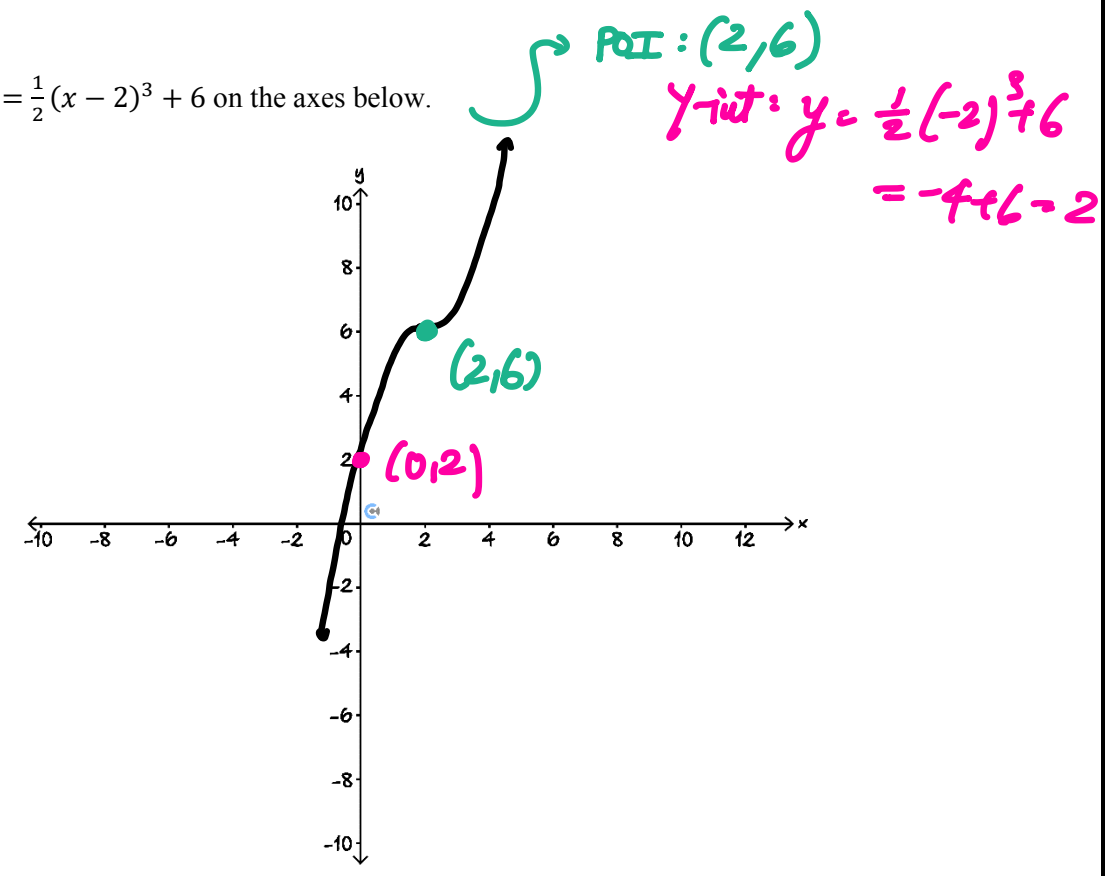
Y-int : $y = (-1)^3 - 5 = -6$

Sketch the graph of $y = (x - 1)^3 - 5$ on the axes below.



Question 25

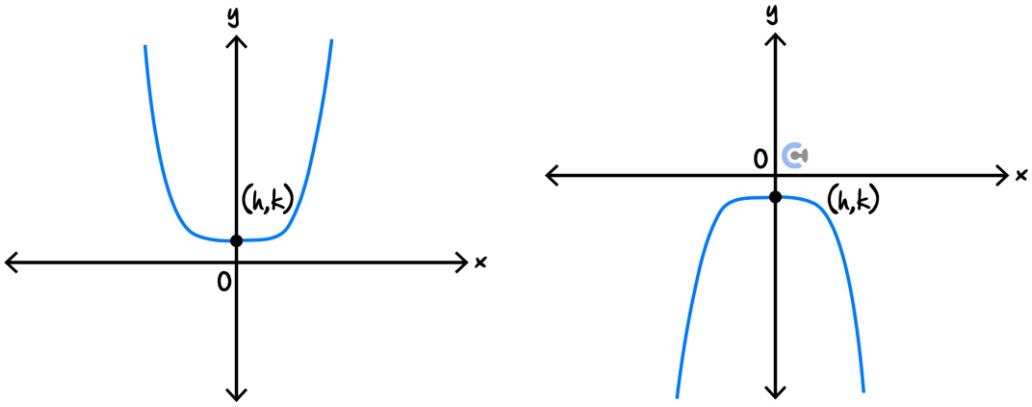
Sketch the graph of $y = \frac{1}{2}(x-2)^3 + 6$ on the axes below.



What about even powers?

Graphs of $a(x-h)^n + k$, where n is an Even Positive Integer

- All graphs look like a "quadratic".

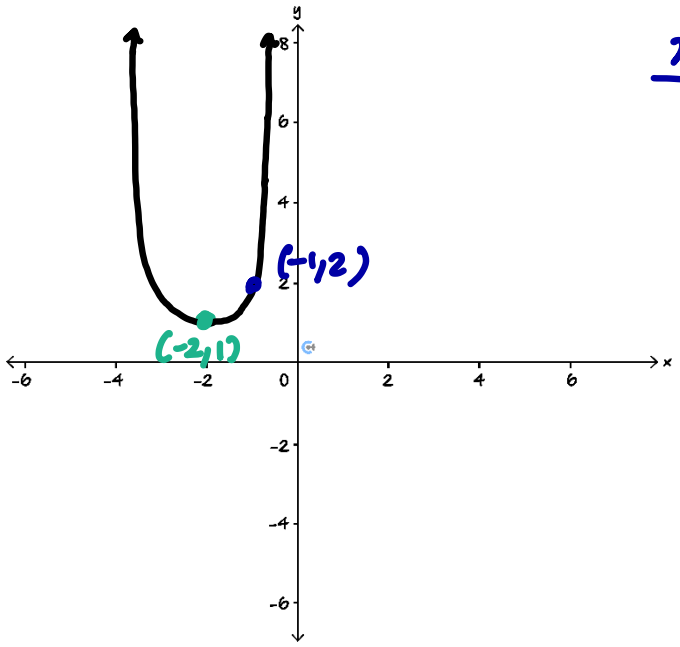


- The point (h, k) gives us the turning point.

Question 26 Walkthrough.

Sketch the graph of $y = (x + 2)^4 + 1$ on the axes below.

TP: $(-2, 1)$ y-int: $y = (2)^4 + 1 = 17$



$x = -1$:

$y = (1)^4 + 1$

$= 2$

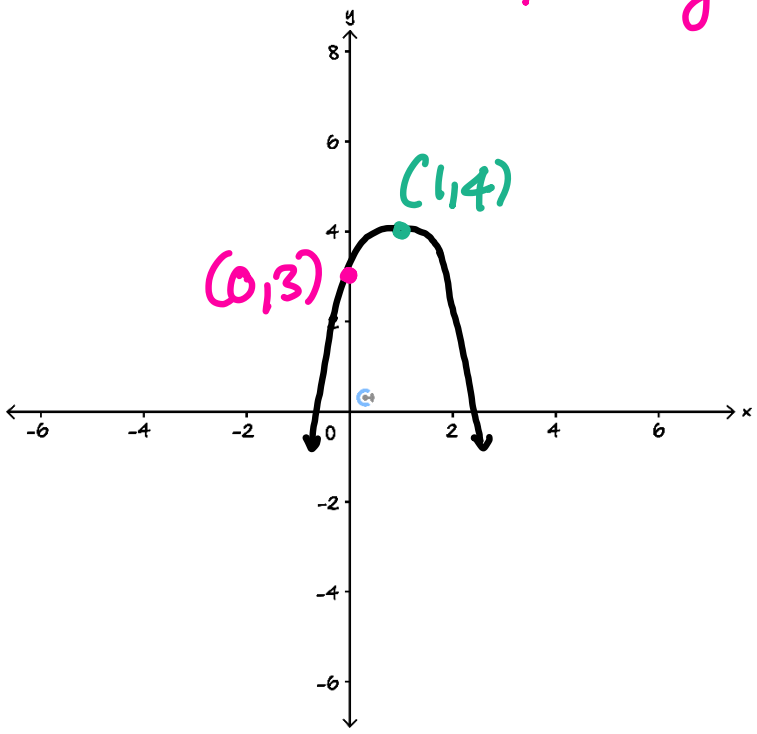
$(-1, 2)$

Question 27

Sketch the graph of $y = -(x - 1)^4 + 4$ on the axes below.

TP: $(1, 4)$

y-int: $y = -(-1)^4 + 4 = 3$

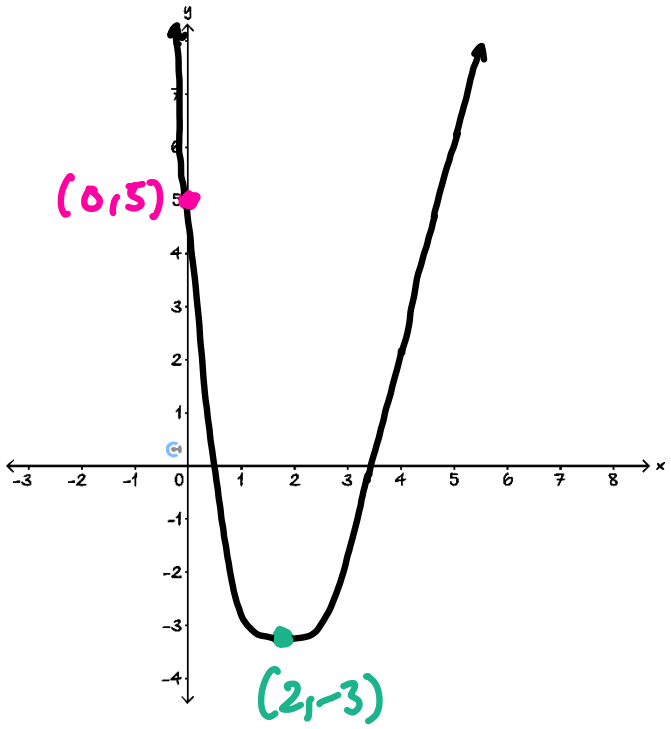


Question 28 Extension.

Sketch the graph of $y = \frac{1}{2}(x-2)^4 - 3$ on the axes below.

TP: (2, -3)

y-int: $y = \frac{1}{2}(-2)^4 - 3$
$= 8 - 3$
$= 5$



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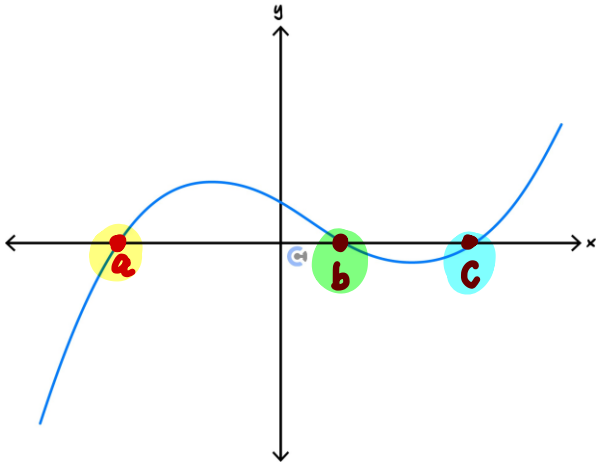
Sub-Section: Graphing Factorised Polynomials

What about the graph of a factorised polynomial?

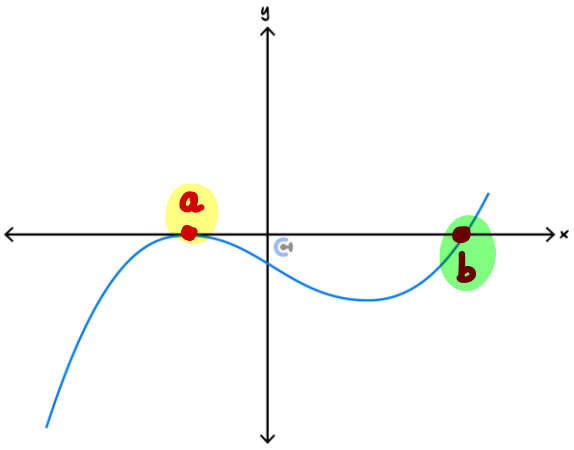
Exploration: Graphs of Factorised Polynomials

All ___non-repeated___ *linear factors correspond to* ___x-intercepts___ *of the graph.*



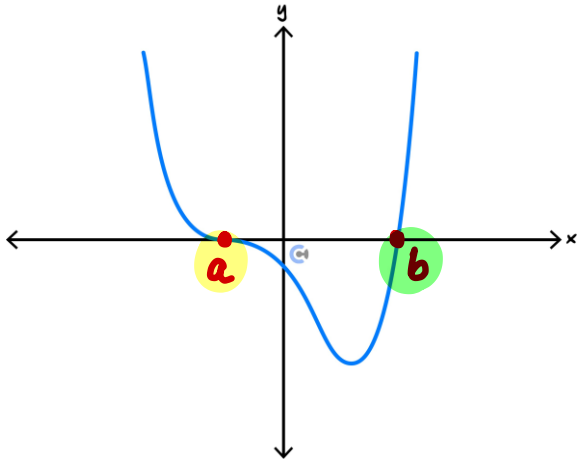
- E.g., $f(x) = (x-a)(x-b)(x-c)$ results in x-intercepts at $(a,0)$, $(b,0)$ and $(c,0)$.

All ___squared___ *linear factors correspond to* ___TP & x-intercept___ *of the graph.*



- E.g., $f(x) = (x-a)^2(x-b)$ will have an x-intercept $(a, 0)$ which is also a local minimum/maximum.

All Cubed *linear factors correspond to* SPOI & x-intercept *of the graph.*



- E.g., $f(x) = (x-a)^3(x-b)$ has an x-intercept $(a, 0)$ which is also a stationary point of inflection.

Definition

Graphs of Factorised Polynomials

- **Steps:**

1. Plot x-intercepts.
2. Determine whether the polynomial is positive or negative.
3. Use the repeated factors to deduce the shape.

   Non-Repeated: Only x-intercept.

   Even Repeated: x-intercept and a turning point.

   Odd Repeated: x-intercept and a stationary point of inflection.

Space for Personal Notes

Question 29 Walkthrough.

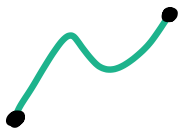
Sketch the graphs of the following functions on the axes provided. Ignore the y-axis scale.

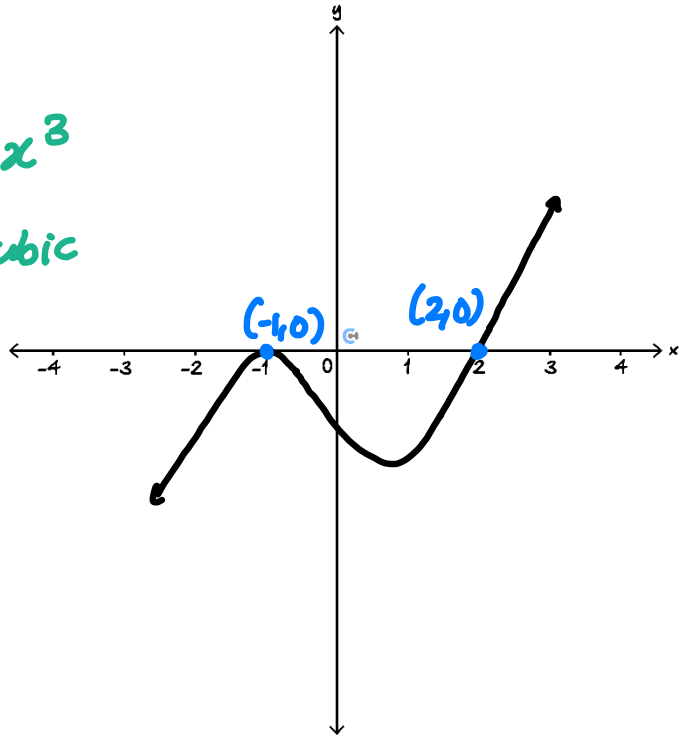
a. $y = (x+1)^2(x-2)$

$x = -1, 2$

$x^2 \cdot x = +x^3$

Shape = +ve cubic



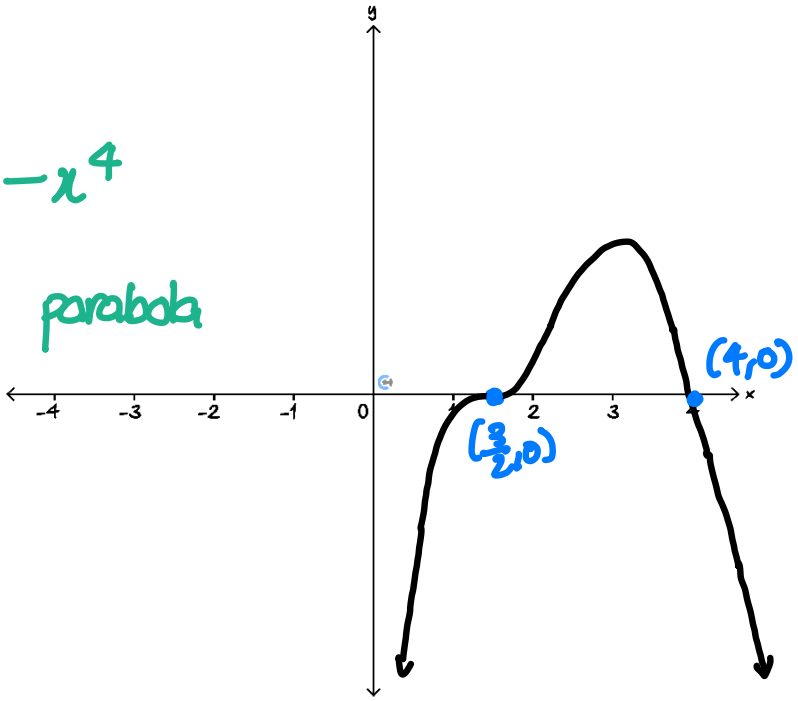


b. $y = \left(x - \frac{3}{2}\right)^3 (4 - x)$

$x = \frac{3}{2}, 4$

$x^3 \cdot -x = -x^4$

Shape = -ve parabola



Your turn!

Question 30

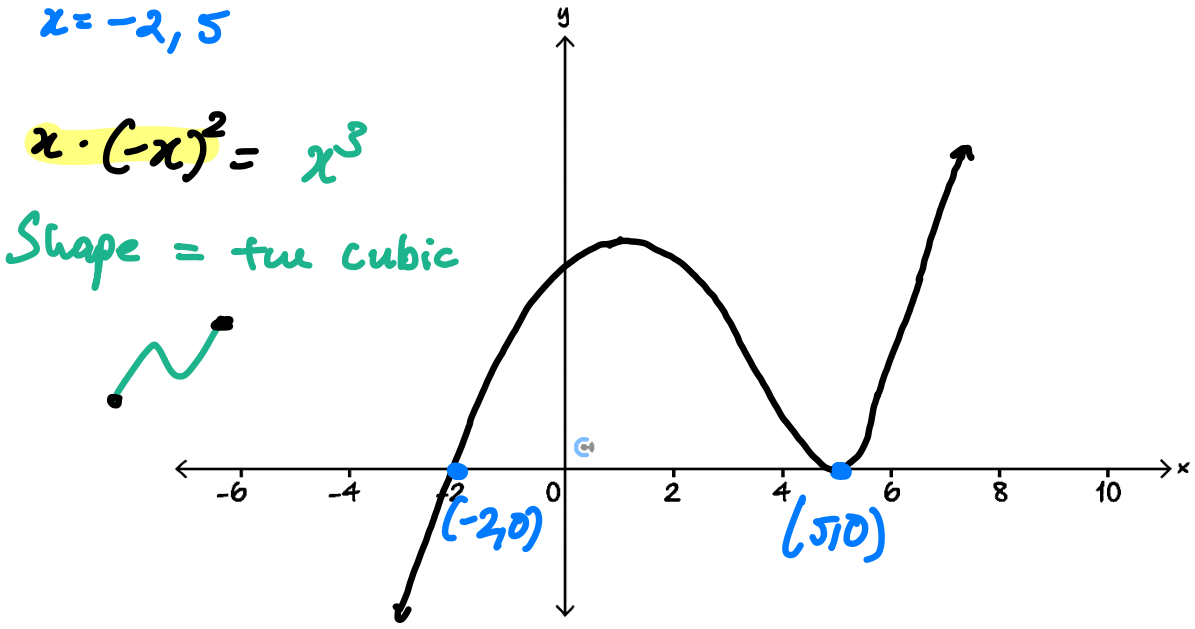
Sketch the graphs of the following functions on the axes provided. Ignore the y-axis scale.

a. $y = (2 + x)(5 - x)^2$

$x = -2, 5$

$x \cdot (-x)^2 = x^3$

Shape = true cubic

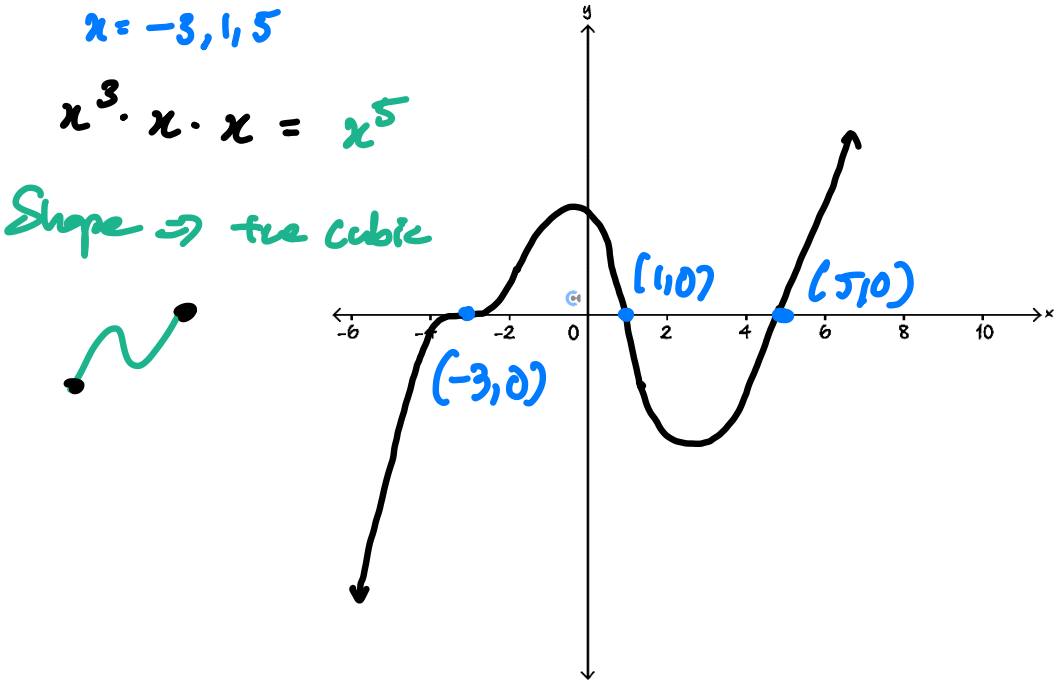


b. $y = (x + 3)^3(x - 1)(x - 5)$

$x = -3, 1, 5$

$x^3 \cdot x \cdot x = x^5$

Shape ⇒ true cubic



Question 31

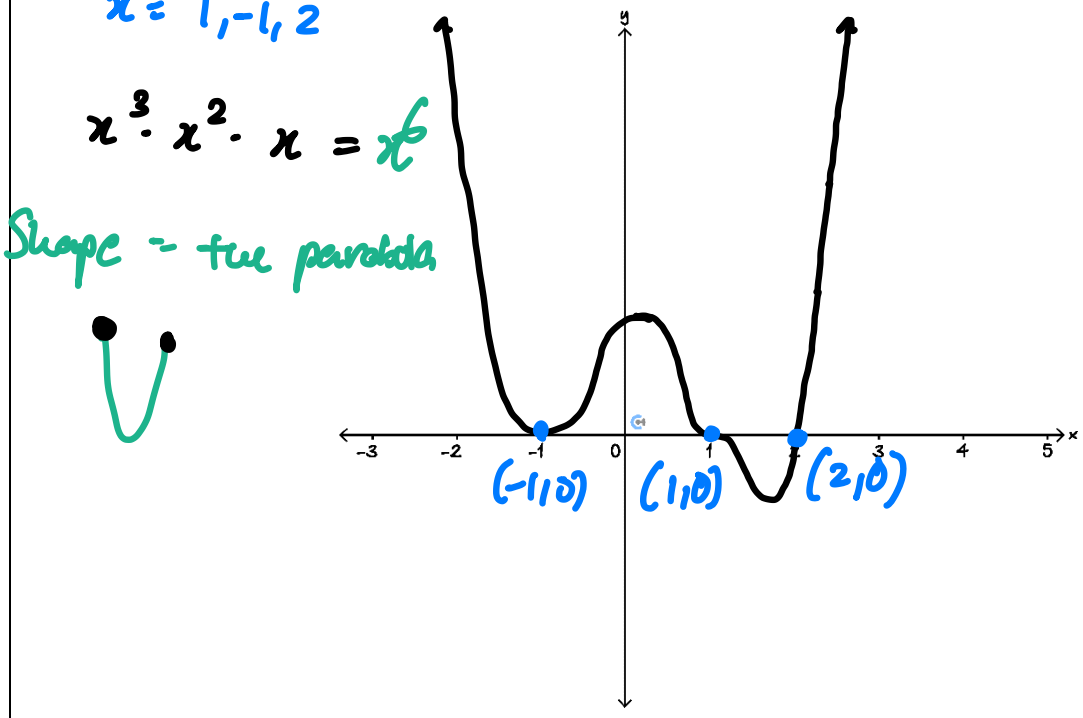
Sketch the graph of the following function on the axes provided. Ignore the y-axis scale.

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

$x = 1, -1, 2$

$x^3 \cdot x^2 \cdot x = x^6$

Shape - true parabola



Space for Personal Notes

Contour Check

Learning Objective: [1.5.1] – Identify the properties of polynomials and solve long division.

Key Takeaways

- The degree of a polynomial is the polynomial's highest power.
- The roots of a polynomial are its x-intercepts.
- For polynomial long division:

$$\frac{Dividend}{Divisor} = Quotient + \frac{Remainder}{Divisor}$$

Learning Objective: [1.5.2] – Apply remainder and factor theorem to find remainders and factors.

Key Takeaways

- When $P(x)$ is divided by $(x - \alpha)$, the remainder is $P(\alpha)$.
- If $P(\alpha) = 0$ then $(x - \alpha)$ is a factor of $P(x)$.

Learning Objective: [1.5.3] - Find factored form of polynomials.

Key Takeaways

- Steps to factor a cubic polynomial are:
  - Find a single root by trial and error.

    (Factor Theorem: Substitute into the function and see if we get zero.)
  - Use long division to find the quadratic factor.
  - Factorise the quadratic.
- Rational Root Theorem **narrows down** the possible roots. If the roots are rational numbers, it must be that any.

$$Potential\ root = \pm \frac{Factors\ of\ \text{constant term}\ a_0}{Factors\ of\ \text{leading coefficient}\ a_n}$$

- Sum and difference of cubes:

$$a^3 + b^3 = (a+b)(a^2 - ab + b^2)$$

$$a^3 - b^3 = (a-b)(a^2 + ab + b^2)$$

Learning Objective: [1.5.4] – Graph factored and unfactored polynomials.

Key Takeaways

- Graphs of $a(x-h)^n+k$, where n is an Odd Positive Integer that is not equal to 1:
  - The point (h,k) gives us the stationary point of inflection.
- Graphs of $a(x-h)^n+k$, where n is an Even Positive Integer:
  - The point (h,k) gives us the TP.
  - These graphs look like a parabola.
- Steps to graphing factorised polynomials:

1. Plot x-intercepts.
2. Determine whether the polynomial is positive or negative.
3. Use the repeated factors to deduce the shape:

   Non-Repeated: Only x-intercept.

   Even Repeated: x-intercept and a TP.

   Odd Repeated: x-intercept and a SPOI (Stationary Point of Inflection).

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