

# VCE Mathematics 3/4 Bound Reference

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**Theorem 1.**  $\{Sam\} \cap \{Bitches\} = \emptyset$

*Proof.*  $\{Sam\} \in$  Samuel Murphy  
 $\{Bitches\} \in$  All Females

A person "Person" is denoted as being a certain sex by the notation: Person<sub>M</sub> or Person<sub>F</sub>

Samuel Murphy = (Samuel Murphy)<sub>M</sub>

A female takes the form of Person<sub>r</sub>. ∴ {Bitches} contains all Person<sub>F</sub>, and exclusively all Person<sub>F</sub>.

The set Sam contains one element (Samuel Murphy)<sub>M</sub>, which does not take the form Person<sub>F</sub> ∴ the sets Sam and Bitches contain no elements in common.

∴  $\{Sam\} \cap \{Bitches\} = \emptyset$  ■

## Mathematical Methods formulas

### Mensuration

area of a trapezium	$\frac{1}{2}(a+b)h$	volume of a pyramid	$\frac{1}{3}Ah$
curved surface area of a cylinder	$2\pi rh$	volume of a sphere	$\frac{4}{3}\pi r^3$
volume of a cylinder	$\pi r^2 h$	area of a triangle	$\frac{1}{2}bc \sin(A)$
volume of a cone	$\frac{1}{3}\pi r^2 h$		

### Calculus

$\frac{d}{dx}(x^n) = nx^{n-1}$	$\int x^n dx = \frac{1}{n+1} x^{n+1} + c, n \neq -1$		
$\frac{d}{dx}((ax+b)^n) = an(ax+b)^{n-1}$	$\int (ax+b)^n dx = \frac{1}{a(n+1)}(ax+b)^{n+1} + c, n \neq -1$		
$\frac{d}{dx}(e^{ax}) = ae^{ax}$	$\int e^{ax} dx = \frac{1}{a} e^{ax} + c$		
$\frac{d}{dx}(\log_e(x)) = \frac{1}{x}$	$\int \frac{1}{x} dx = \log_e(x) + c, x > 0$		
$\frac{d}{dx}(\sin(ax)) = a \cos(ax)$	$\int \sin(ax) dx = -\frac{1}{a} \cos(ax) + c$		
$\frac{d}{dx}(\cos(ax)) = -a \sin(ax)$	$\int \cos(ax) dx = \frac{1}{a} \sin(ax) + c$		
$\frac{d}{dx}(\tan(ax)) = \frac{a}{\cos^2(ax)} = a \sec^2(ax)$			
product rule	$\frac{d}{dx}(uv) = u \frac{dv}{dx} + v \frac{du}{dx}$	quotient rule	$\frac{d}{dx}\left(\frac{u}{v}\right) = \frac{v \frac{du}{dx} - u \frac{dv}{dx}}{v^2}$
chain rule	$\frac{dy}{dx} = \frac{dy}{du} \frac{du}{dx}$	Newton's method	$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}$
trapezium rule approximation	$Area \approx \frac{x_n - x_0}{2n} \left[ f(x_0) + 2f(x_1) + 2f(x_2) + \dots + 2f(x_{n-2}) + 2f(x_{n-1}) + f(x_n) \right]$		

## Probability

$\Pr(A) = 1 - \Pr(A')$		$\Pr(A \cup B) = \Pr(A) + \Pr(B) - \Pr(A \cap B)$	
$\Pr(A B) = \frac{\Pr(A \cap B)}{\Pr(B)}$			
mean	$\mu = E(X)$	variance	$\text{var}(X) = \sigma^2 = E((X - \mu)^2) = E(X^2) - \mu^2$
binomial coefficient	$\binom{n}{x} = \frac{n!}{x!(n-x)!}$		

Probability distribution		Mean	Variance
discrete	$\Pr(X = x) = p(x)$	$\mu = \sum x p(x)$	$\sigma^2 = \sum (x - \mu)^2 p(x)$
binomial	$\Pr(X = x) = \binom{n}{x} p^x (1-p)^{n-x}$	$\mu = np$	$\sigma^2 = np(1-p)$
continuous	$\Pr(a < X < b) = \int_a^b f(x) dx$	$\mu = \int_{-\infty}^{\infty} x f(x) dx$	$\sigma^2 = \int_{-\infty}^{\infty} (x - \mu)^2 f(x) dx$

## Sample proportions

$\hat{P} = \frac{X}{n}$		mean	$E(\hat{P}) = p$
standard deviation	$\text{sd}(\hat{P}) = \sqrt{\frac{p(1-p)}{n}}$	approximate confidence interval	$\left( \hat{p} - z \sqrt{\frac{\hat{p}(1-\hat{p})}{n}}, \hat{p} + z \sqrt{\frac{\hat{p}(1-\hat{p})}{n}} \right)$

**Mensuration**

area of a circle segment	$\frac{r^2}{2}(\theta - \sin(\theta))$	volume of a sphere	$\frac{4}{3}\pi r^3$
volume of a cylinder	$\pi r^2 h$	area of a triangle	$\frac{1}{2}bc \sin(A)$
volume of a cone	$\frac{1}{3}\pi r^2 h$	sine rule	$\frac{a}{\sin(A)} = \frac{b}{\sin(B)} = \frac{c}{\sin(C)}$
volume of a pyramid	$\frac{1}{3}Ah$	cosine rule	$c^2 = a^2 + b^2 - 2ab \cos(C)$

**Calculus – continued**

$\frac{d}{dx}(x^n) = nx^{n-1}$	$\int x^n dx = \frac{1}{n+1}x^{n+1} + c, n \neq -1$	product rule	$\frac{d}{dx}(uv) = u \frac{dv}{dx} + v \frac{du}{dx}$
$\frac{d}{dx}(e^{ax}) = ae^{ax}$	$\int e^{ax} dx = \frac{1}{a}e^{ax} + c$	quotient rule	$\frac{d}{dx}\left(\frac{u}{v}\right) = \frac{v}{\cancel{dx}} \frac{du}{\cancel{v}} - u \frac{dv}{\cancel{dx}}$
$\frac{d}{dx}(\log_e(x)) = \frac{1}{x}$	$\int \frac{1}{x} dx = \log_e x  + c$	chain rule	$\frac{dy}{dx} = \frac{dy}{du} \times \frac{du}{dx}$
$\frac{d}{dx}(\sin(ax)) = a \cos(ax)$	$\int \sin(ax) dx = -\frac{1}{a} \cos(ax) + c$	integration by parts	$\int u \frac{dv}{dx} dx = uv - \int v \frac{du}{dx} dx$
$\frac{d}{dx}(\cos(ax)) = -a \sin(ax)$	$\int \cos(ax) dx = \frac{1}{a} \sin(ax) + c$	Euler's method	If $\frac{dy}{dx} = f(x, y)$ , $x_0 = a$ and $y_0 = b$ , then $x_{n+1} = x_n + h$ and $y_{n+1} = y_n + h \times f(x_n, y_n)$ .
$\frac{d}{dx}(\tan(ax)) = a \sec^2(ax)$	$\int \sec^2(ax) dx = \frac{1}{a} \tan(ax) + c$		
$\frac{d}{dx}(\cot(ax)) = -a \operatorname{cosec}^2(ax)$	$\int \operatorname{cosec}^2(ax) dx = -\frac{1}{a} \cot(ax) + c$	arc length parametric	$\int_{t_1}^{t_2} \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt$
$\frac{d}{dx}(\sec(ax)) = a \sec(ax) \tan(ax)$	$\int \sec(ax) \tan(ax) dx = \frac{1}{a} \sec(ax) + c$	surface area Cartesian about x-axis	$\int_{x_1}^{x_2} 2\pi y \sqrt{1 + \left(\frac{dy}{dx}\right)^2} dx$
$\frac{d}{dx}(\operatorname{cosec}(ax)) = -a \operatorname{cosec}(ax) \cot(ax)$	$\int \operatorname{cosec}(ax) \cot(ax) dx = -\frac{1}{a} \operatorname{cosec}(ax) + c$	surface area Cartesian about y-axis	$\int_{y_1}^{y_2} 2\pi x \sqrt{1 + \left(\frac{dx}{dy}\right)^2} dy$
$\frac{d}{dx}(\sin^{-1}(ax)) = \frac{a}{\sqrt{1-(ax)^2}}$	$\int \frac{1}{\sqrt{a^2-x^2}} dx = \sin^{-1}\left(\frac{x}{a}\right) + c, a > 0$	surface area parametric about x-axis	$\int_{t_1}^{t_2} 2\pi y \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt$
$\frac{d}{dx}(\cos^{-1}(ax)) = \frac{-a}{\sqrt{1-(ax)^2}}$	$\int \frac{-1}{\sqrt{a^2-x^2}} dx = \cos^{-1}\left(\frac{x}{a}\right) + c, a > 0$	surface area parametric about y-axis	$\int_{t_1}^{t_2} 2\pi x \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt$
$\frac{d}{dx}(\tan^{-1}(ax)) = \frac{a}{1+(ax)^2}$	$\int \frac{a}{a^2+x^2} dx = \tan^{-1}\left(\frac{x}{a}\right) + c$	<b>Kinematics</b>	
$\operatorname{E}(aX_1 + b) = a \operatorname{E}(X_1) + b$ for independent random variables $X_1, X_2, \dots, X_n$	$\operatorname{E}(a_1X_1 + a_2X_2 + \dots + a_nX_n) = a_1\operatorname{E}(X_1) + a_2\operatorname{E}(X_2) + \dots + a_n\operatorname{E}(X_n)$	acceleration	$a = \frac{d^2x}{dt^2} - \frac{dv}{dt} = v \frac{dv}{dx} - \frac{d}{dx}\left(\frac{1}{2}v^2\right)$
$\operatorname{Var}(aX_1 + b) = a^2\operatorname{Var}(X_1)$ for independent identically distributed variables $X_1, X_2, \dots, X_n$	$\operatorname{Var}(a_1X_1 + a_2X_2 + \dots + a_nX_n) = a_1^2\operatorname{Var}(X_1) + a_2^2\operatorname{Var}(X_2) + \dots + a_n^2\operatorname{Var}(X_n)$	v = $u + at$	$s = ut + \frac{1}{2}at^2$
$\operatorname{Var}(X_1 + X_2 + \dots + X_n) = n\mu^2$ approximate confidence interval for $\mu$	$\left(\bar{X} - z \frac{s}{\sqrt{n}}, \bar{X} + z \frac{s}{\sqrt{n}}\right)$	constant acceleration formulas	$v^2 = u^2 + 2as$
distribution of sample mean $\bar{X}$	mean variance $\operatorname{Var}(\bar{X}) = \frac{\sigma^2}{n}$		$s = \frac{1}{2}(u+v)t$

**Data analysis, probability and statistics**

$\operatorname{E}(aX_1 + b) = a \operatorname{E}(X_1) + b$ for independent random variables $X_1, X_2, \dots, X_n$	$\operatorname{E}(a_1X_1 + a_2X_2 + \dots + a_nX_n) = a_1\operatorname{E}(X_1) + a_2\operatorname{E}(X_2) + \dots + a_n\operatorname{E}(X_n)$
$\operatorname{Var}(aX_1 + b) = a^2\operatorname{Var}(X_1)$ for independent identically distributed variables $X_1, X_2, \dots, X_n$	$\operatorname{Var}(a_1X_1 + a_2X_2 + \dots + a_nX_n) = a_1^2\operatorname{Var}(X_1) + a_2^2\operatorname{Var}(X_2) + \dots + a_n^2\operatorname{Var}(X_n)$
$\operatorname{E}(X_1 + X_2 + \dots + X_n) = n\mu$	$\operatorname{Var}(X_1 + X_2 + \dots + X_n) = n\sigma^2$
approximate confidence interval for $\mu$	$\left(\bar{X} - z \frac{s}{\sqrt{n}}, \bar{X} + z \frac{s}{\sqrt{n}}\right)$
distribution of sample mean $\bar{X}$	mean variance $\operatorname{Var}(\bar{X}) = \frac{\sigma^2}{n}$

## Vectors in two and three dimensions

$\underline{r}(t) = x(t)\underline{i} + y(t)\underline{j} + z(t)\underline{k}$	$ \underline{r}(t)  = \sqrt{x(t)^2 + y(t)^2 + z(t)^2}$
	$\dot{\underline{r}}(t) = \frac{d\underline{r}}{dt} = \frac{dx}{dt}\underline{i} + \frac{dy}{dt}\underline{j} + \frac{dz}{dt}\underline{k}$
for $\underline{r}_1 = x_1\underline{i} + y_1\underline{j} + z_1\underline{k}$ and $\underline{r}_2 = x_2\underline{i} + y_2\underline{j} + z_2\underline{k}$	<p>vector scalar product  <math>\underline{r}_1 \cdot \underline{r}_2 =  \underline{r}_1   \underline{r}_2  \cos(\theta) = x_1x_2 + y_1y_2 + z_1z_2</math></p> <p>vector cross product  <math>\underline{r}_1 \times \underline{r}_2 = \begin{vmatrix} \underline{i} &amp; \underline{j} &amp; \underline{k} \\ x_1 &amp; y_1 &amp; z_1 \\ x_2 &amp; y_2 &amp; z_2 \end{vmatrix} = (y_1z_2 - y_2z_1)\underline{i} + (x_2z_1 - x_1z_2)\underline{j} + (x_1y_2 - x_2y_1)\underline{k}</math></p>
vector equation of a line	$\underline{r}(t) = \underline{r}_1 + t\underline{r}_2 = (x_1 + x_2t)\underline{i} + (y_1 + y_2t)\underline{j} + (z_1 + z_2t)\underline{k}$
parametric equation of a line	$x(t) = x_1 + x_2t \quad y(t) = y_1 + y_2t \quad z(t) = z_1 + z_2t$
vector equation of a plane	$\underline{r}(s, t) = \underline{r}_0 + s\underline{r}_1 + t\underline{r}_2 = (x_0 + x_1s + x_2t)\underline{i} + (y_0 + y_1s + y_2t)\underline{j} + (z_0 + z_1s + z_2t)\underline{k}$
parametric equation of a plane	$x(s, t) = x_0 + x_1s + x_2t, \quad y(s, t) = y_0 + y_1s + y_2t, \quad z(s, t) = z_0 + z_1s + z_2t$
Cartesian equation of a plane	$ax + by + cz = d$

## Circular functions

$\cos^2(x) + \sin^2(x) = 1$	
$1 + \tan^2(x) = \sec^2(x)$	$\cot^2(x) + 1 = \operatorname{cosec}^2(x)$
$\sin(x + y) = \sin(x) \cos(y) + \cos(x) \sin(y)$	$\sin(x - y) = \sin(x) \cos(y) - \cos(x) \sin(y)$
$\cos(x + y) = \cos(x) \cos(y) - \sin(x) \sin(y)$	$\cos(x - y) = \cos(x) \cos(y) + \sin(x) \sin(y)$
$\tan(x + y) = \frac{\tan(x) + \tan(y)}{1 - \tan(x)\tan(y)}$	$\tan(x - y) = \frac{\tan(x) - \tan(y)}{1 + \tan(x)\tan(y)}$
$\sin(2x) = 2 \sin(x) \cos(x)$	
$\cos(2x) = \cos^2(x) - \sin^2(x) = 2 \cos^2(x) - 1 = 1 - 2 \sin^2(x)$	$\tan(2x) = \frac{2 \tan(x)}{1 - \tan^2(x)}$
$\sin^2(ax) = \frac{1}{2}(1 - \cos(2ax))$	$\cos^2(ax) = \frac{1}{2}(1 + \cos(2ax))$

## Contents

<b>1 Useful Rules, Values and Identities</b>	<b>9</b>
1.1 TI Nspire Shortcut Keys . . . . .	9
1.2 Functions . . . . .	9
<b>2 Silly Blunders</b>	<b>10</b>
<b>3 Unit 1/2 Assumed Knowledge</b>	<b>10</b>
3.1 Sequences and Series . . . . .	10
3.2 Non-Linear Relations . . . . .	10
3.2.1 Circles . . . . .	10
3.2.2 Ellipses . . . . .	11
3.2.3 Hyperbolas . . . . .	11
<b>4 Functions</b>	<b>11</b>
4.1 Tech . . . . .	11
4.1.1 fMax(rule,iv,lower,upper) and fMin(rule,iv,lower,upper) . . . . .	11
4.1.2 tangentLine(rule,iv,x) . . . . .	12
4.1.3 normalLine(rule,iv,x) . . . . .	12
4.1.4 scriptedmath\poi(f(x),x) . . . . .	12
4.1.5 scriptedmath\inv(f(x),pointX) . . . . .	12
4.2 Average Value and Average Rate . . . . .	12
4.3 Transformations . . . . .	12
4.4 Composite Functions . . . . .	12
4.5 Exponential Functions . . . . .	13
4.6 Simultaneous Unique Solutions . . . . .	13
4.7 Tangents . . . . .	14
4.8 Areas . . . . .	14
<b>5 Vectors and Kinematics</b>	<b>15</b>
5.1 Vectors Tech . . . . .	15
5.1.1 norm(a) . . . . .	15
5.1.2 unitV(a) . . . . .	15
5.1.3 dotP(a,b) . . . . .	15
5.1.4 crossP(a,b) . . . . .	15
5.1.5 sam_vectors\vang(a,b) . . . . .	16
5.1.6 sam_vectors\vecres(a,b) . . . . .	16
5.1.7 sam_vectors\lindep(a,b,c,p) . . . . .	16
5.2 Angles Between Vectors . . . . .	16
5.3 Linear Dependence . . . . .	16
5.4 Scalar Product . . . . .	17
5.5 Vector and Scalar Resolutes . . . . .	17
5.6 Vector Proofs . . . . .	17
5.6.1 Collinearity . . . . .	17
5.7 Vector Equations . . . . .	19
5.8 Intersections and Skew Lines . . . . .	19
5.8.1 Lines in 2D Space . . . . .	19
5.8.2 Lines in 3D Space . . . . .	19
5.9 Vector Product (Cross Product) . . . . .	20
5.10 Vector Equations of Planes . . . . .	20
5.11 Distances, Angles, Intersections of Planes . . . . .	22
5.11.1 Distances . . . . .	22
5.11.2 Intersections and Angles . . . . .	23
5.11.3 Intersection of Planes . . . . .	23
5.12 Parametric Vector Equations . . . . .	24
5.13 SUVAT and Constant Acceleration . . . . .	24
5.14 Terminal (Limiting) Velocity . . . . .	24
5.15 Velocity Functions of Time . . . . .	24
5.16 Velocity-Time Graphs . . . . .	25
5.17 Vector Functions . . . . .	25
5.17.1 Describing Particle's Path . . . . .	25
5.17.2 Describing Curves with Vector Functions . . . . .	25
5.18 Position Vectors as a Function of Time . . . . .	25
5.19 Vector Calculus . . . . .	26
5.19.1 Properties of Vector Derivatives . . . . .	26
5.19.2 Vector Antidifferentiation . . . . .	26
5.19.3 Velocity and Acceleration Along a Curve . . . . .	26
5.19.4 Alternative Forms of Acceleration . . . . .	26

---

<b>6 Complex Numbers</b>	<b>27</b>
6.1 Tech . . . . .	27
6.1.1 Lines in the Complex Plane . . . . .	27
6.1.2 Relations with Arguments in the Complex Plane . . . . .	27
6.2 Operations of Complex Numbers in Cartesian Form . . . . .	27
6.3 Properties of Conjugates . . . . .	28
6.4 Polar Form Operations . . . . .	28
6.5 Quadratics over Complex Numbers . . . . .	29
6.6 Polynomials over Complex Numbers . . . . .	29
6.7 Solving with De Moivre . . . . .	29
6.8 Subsets of Complex Plane . . . . .	30
6.8.1 Circles . . . . .	30
6.8.2 Lines . . . . .	30
6.8.3 Rays . . . . .	31
6.8.4 Hyperbolas . . . . .	31
6.8.5 Intersections of Subsets . . . . .	31
<b>7 Logic and Proof</b>	<b>31</b>
7.1 Converses, Negations, Contrapositives . . . . .	31
7.2 Proof of Equivalent Statements . . . . .	32
7.3 Proof by Contradiction . . . . .	32
7.4 Quantifiers and Counterexamples . . . . .	32
7.4.1 Negations with Quantifiers . . . . .	32
7.5 Product and Sum Notation . . . . .	32
7.6 Direct Proof . . . . .	32
7.7 Proof by Contradiction . . . . .	32
7.8 Arithmetic Mean-Geometric Mean Inequality . . . . .	33
7.9 Proof by Induction . . . . .	34
<b>8 Circular Functions</b>	<b>35</b>
8.1 Tech . . . . .	35
8.2 Inverse Circular Functions . . . . .	35
8.3 Symmetry Properties . . . . .	36
8.4 Solutions of Equations with Circular Functions . . . . .	36
8.5 Product-to-sum identities . . . . .	37
8.6 Sum-to-product identities . . . . .	37
<b>9 Stats and Probability :skull:</b>	<b>37</b>
9.1 Tech . . . . .	37
9.1.1 sam_prob\bp{d}(n,p,lower,upper) . . . . .	37
9.1.2 sam_prob\pd{anal}(x,px) . . . . .	37
9.1.3 scriptedmath\expec(f(x),x) . . . . .	37
9.1.4 scriptedmath\var(f(x),x) . . . . .	37
9.1.5 scriptedmath\sd(f(x),x) . . . . .	37
9.1.6 scriptedmath\mode(list,freqlist) . . . . .	37
9.1.7 scriptedmath\ns(eq,var) . . . . .	37
9.1.8 normcdf(lower, upper, $\mu$ , $\sigma$ ) . . . . .	37
9.1.9 invnorm(left tail prob, $\mu$ , $\sigma$ ) . . . . .	37
9.1.10 binomcdf(n, p, lower, upper) . . . . .	37
9.1.11 binompdf(n, p, x) . . . . .	37
9.1.12 invbinomn(cumulative prob, prob, numsuccess) . . . . .	37
9.1.13 sam_prob\normsum(x1,ltp1,x2,ltp2) . . . . .	37
9.1.14 Determine the Mean and Standard Deviation of a Normal Distribution . . . . .	38
9.1.15 Simulating Sample Means . . . . .	38
9.1.16 Confidence Interval (Spesh) . . . . .	38
9.1.17 Determine a Confidence Interval (Methods) . . . . .	38
9.1.18 Hypothesis Testing - One Tail . . . . .	38
9.1.19 nSolve for brute force solving . . . . .	38
9.1.20 Type II Error Probability . . . . .	39
9.2 Linear Functions of Random Variables . . . . .	39
9.3 Independent Events . . . . .	39
9.4 Mutually Exclusive Events . . . . .	39
9.5 Linear Combination of Random Variables . . . . .	39
9.6 Discrete Probability . . . . .	40
9.7 Normal Probability . . . . .	41
9.8 The Binomial Distribution . . . . .	45
9.8.1 Inverse Binomial . . . . .	45
9.9 Sample Means . . . . .	46
9.10 Normal Approximation of Sample Proportions . . . . .	46

---

9.11 Sample Proportions $\hat{P}$ without Normal Approximation (Methods) . . . . .	47
9.12 Distribution of the sample mean . . . . .	48
9.12.1 Central Limit Theorem . . . . .	48
9.12.2 Normal Approximation to the Binomial Distribution . . . . .	48
9.13 Confidence Intervals for the Population Mean . . . . .	48
9.14 Hypothesis Testing for Mean . . . . .	49
9.14.1 One-tail tests . . . . .	49
9.14.2 Two-tail tests . . . . .	49
9.14.3 Relation to Confidence Intervals . . . . .	50
9.14.4 Hypothesis Testing Errors . . . . .	50
<b>10 Differential Calculus</b> . . . . .	<b>62</b>
10.1 Derivatives of $x=f(y)$ . . . . .	62
10.2 Derivatives of Inverse Circular Functions . . . . .	62
10.3 Second Derivatives . . . . .	62
10.4 Points of Inflection . . . . .	62
10.5 Related Rates . . . . .	62
10.6 Rational Functions . . . . .	62
<b>11 Integral Calculus</b> . . . . .	<b>62</b>
11.1 Rules . . . . .	62
11.1.1 Definite Integral . . . . .	62
11.2 Inverse Circular Functions . . . . .	62
11.3 u-Sub . . . . .	62
11.4 Integration by Trig Identities . . . . .	64
11.5 Partial Fractions . . . . .	64
11.6 Integration by Parts . . . . .	64
11.7 Properties of the Definite Integral . . . . .	65
11.8 Area Between Curves . . . . .	65
11.9 Volumes of Solids of Revolution . . . . .	65
11.10 Lengths of Curves in Plane . . . . .	66
11.11 Areas of Surfaces of Revolution . . . . .	67
11.12 Reduction Formulas . . . . .	67
<b>12 Differential Equations</b> . . . . .	<b>68</b>
12.1 Tech . . . . .	68
12.1.1 deSolve(diffeq,iv,dv) . . . . .	68
12.1.2 euler(dydx,iv,dv,{x0,x1},y0,h) . . . . .	68
12.2 Verification of Solutions . . . . .	68
12.3 Proportionality/Inverse Proportionality . . . . .	68
12.4 Logistic DiffEq . . . . .	68
12.5 Separation of Variables . . . . .	69
12.5.1 Solving . . . . .	70
12.6 DiffEqs + Related Rates Crossover Event . . . . .	70
12.7 Definite Integration to solve DiffEqs . . . . .	71
12.8 Newton's Law of Cooling DiffEq . . . . .	76
12.9 Applications of DiffEqs - Concentration Problems . . . . .	76
12.10 Euler's Method . . . . .	76
12.10.1 Over/Underestimates . . . . .	76
12.11 Slope Fields . . . . .	77
12.12 Finding Solutions to DiffEqs . . . . .	77
<b>13 Pseudocode</b> . . . . .	<b>77</b>
13.1 Syntax . . . . .	77
13.2 Example Algorithms . . . . .	77
<b>14 Other Tech</b> . . . . .	<b>79</b>
14.1 Functions . . . . .	79
14.1.1 scriptedmath\poi(f(x),x) . . . . .	79
14.1.2 scriptedmath\inv(f(x),pointX) . . . . .	79
14.1.3 sam_other\newtonraphson(f,g,e,n) . . . . .	79
14.2 Parametric Functions . . . . .	79
14.2.1 scriptedmath\pder(vfunc, parameter) . . . . .	79
<b>15 Advanced Maths</b> . . . . .	<b>79</b>
15.1 The Derivative of $f(x)=4x+1$ . . . . .	79
15.1.1 Our Table of Laplace Transforms . . . . .	80
15.2 Sandwich Theorem . . . . .	80
<b>16 Cheeky Snack</b> . . . . .	<b>85</b>

# 1 Useful Rules, Values and Identities

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

$$\begin{array}{lll} \sin \frac{\pi}{4} = \frac{1}{\sqrt{2}} & \cos \frac{\pi}{4} = \frac{1}{\sqrt{2}} & \tan \frac{\pi}{4} = 1 \\ \sin \frac{\pi}{3} = \frac{\sqrt{3}}{2} & \cos \frac{\pi}{3} = \frac{1}{2} & \tan \frac{\pi}{3} = \sqrt{3} \\ \sin \frac{\pi}{6} = \frac{1}{2} & \cos \frac{\pi}{6} = \frac{\sqrt{3}}{2} & \tan \frac{\pi}{6} = \frac{1}{\sqrt{3}} \end{array}$$

## 1.1 TI Nspire Shortcut Keys

Shortcut	Outcome
ctrl+A	Selects all
ctrl+C	Copy
ctrl+I	Insert page
ctrl+N	New doc
ctrl+O	Open
ctrl+1	Page down (END)
ctrl+space	Underscore
Pi	$\pi$
Theta	$\theta$
Infinity	$\infty$

**Add a Problem** If you want to add a new problem to the document, go doc+4+1

**Add row to matrix** Carriage return key

## 1.2 Functions

**Odd Function**  $f(-x) = -f(x)$ . Odd functions have rotational symmetry about the origin.

**Even Function**  $f(-x) = f(x)$ . Even functions are symmetrical about the  $y$ -axis.

**Sum Functions**  $(f+g)(x) = f(x) + g(x)$ .  $\text{dom } (f+g) = \text{dom } f \cap \text{dom } g$

**Product Functions**  $(fg)(x) = f(x)g(x)$ .  $\text{dom } (fg) = \text{dom } f \cap \text{dom } g$

**Composite Functions**  $g \circ f(x) = g(f(x))$ .  $\text{dom } (g \circ f) = \text{dom } f$

**Inverse Functions**  $f(f^{-1}(x)) = x$

## 2 Silly Blunders

**u-sub** For definite integrals, do not forget to change the limits with the rule of u.

**Linear combinations of random variables - standard deviation** For calculating  $\text{sd}(aX \pm bY)$  always add the variances first through  $a^2\text{Var}(X) + b^2\text{Var}(Y)$ . Only ever find standard deviation through the square root of the variance.

**Kinematics - acceleration** Do not forget to multiply  $\frac{dv}{dx}$  by  $v$  again.

**Integration notation** Don't be an idiot. Remember the  $dx$  on an integral. (CornChip Blunder)

**Complex polynomials** When it asks for a solution for  $z$ , don't write  $z = 2$ , write  $z = 2$ . Solutions are equations for  $z$  that lead to  $P(z) = 0$ . Do not list factors when it asks for solutions. (CornChip Blunder)

**Cuboid** A cuboid is not a cube. You're sped.

**Decimals** Questions ask for decimal answers. Check this.

**Percentages** Probability or sample statistic questions may ask for a percentage proportion. DO NOT GIVE THE PROBABILITY (0.69), GIVE THEM THE PERCENTAGE (69%).

**MCQs about Stats** Some MCQs may ask about the variance of a variable or the standard deviation. Give them which one they ask for!!

**Domains of Inverse** Usually when they ask you to find an inverse function, they want you to find its domain as well. Watch out for this!

**Magnitude of Scalar Resolute** The expression  $\frac{1}{|b|}|b \cdot a|$  is the **magnitude** of the scalar resolute, not just the scalar resolute.

## 3 Unit 1/2 Assumed Knowledge

### 3.1 Sequences and Series

**Arithmetic Sequences** Sequences formed by adding a fixed amount to successive terms.

$$t_n = a + (n - 1)d$$

$a$  is the first term in the sequence,  $d$  is the common difference.

**Arithmetic Series** The sum of an arithmetic sequence.

$$S_n = \frac{n}{2} (2a + (n - 1)d)$$

**Geometric Sequences** Sequences formed by multiplying successive terms by a fixed ratio.

$$t_n = ar^{n-1}$$

$a$  is the first term,  $r$  is the common ratio  $r = \frac{t_k}{t_{k-1}}$  for  $k > 1$

**Geometric Series** The sum of terms in a geometric sequence.

$$S_n = \frac{a(1 - r^n)}{1 - r}$$

**Infinite Geometric Series**

$$S_\infty = \frac{a}{1 - r} \quad -1 < r < 1$$

### 3.2 Non-Linear Relations

#### 3.2.1 Circles

$$(x - h)^2 + (y - k)^2 = r^2$$

Represents a circle of radius  $r$  centred on  $(h, k)$ .

### 3.2.2 Ellipses

$$\frac{(x-h)^2}{a^2} + \frac{(y-k)^2}{b^2} = 1$$

Ellipse with centre  $(h, k)$  and  $2a$  is the horizontal axis length,  $2b$  is the vertical axis length.

### 3.2.3 Hyperbolas

$$\frac{(x-h)^2}{a^2} - \frac{(y-k)^2}{b^2} = 1 \quad \text{Asymptotes: } y - k = \pm \frac{b}{a}(x - h)$$

Hyperbola with centre  $(h, k)$  and  $2a$  is the horizontal distance between foci,  $2b$  is a vertical dilation. The tangents

#### Exam-style Question: VCAA 2007 Spesh E2 A1

A hyperbola has equation  $\frac{(x-2)^2}{a^2} - \frac{4(y+3)^2}{a^2} = 1$ , where  $a \in \mathbb{R} \setminus \{0\}$ . The product of the gradients of the asymptotes is:

$$\frac{(x-2)^2}{a^2} - \frac{4(y+3)^2}{a^2} = \frac{(x-2)^2}{a^2} - \frac{(y+3)^2}{\left(\frac{a}{2}\right)^2} = 1$$

Asymptotes are  $y + 3 = \pm \frac{a}{2}(x - 2) = \pm \frac{1}{2}(x - 2)$  and the product of the gradients is  $\frac{1}{2} \times \left(-\frac{1}{2}\right) = -\frac{1}{4}$ .

#### Exam-style Question: 2015 MAV Spesh E2 A1

At what points do the asymptotes of the hyperbola with equation  $\frac{(y+2)^2}{2^2} - \frac{(x-1)^2}{4^2} = 1$  intersect with the line  $y = 3$ ?

The asymptotes are given by  $x - 1 = \pm \frac{4}{2}(y + 2)$ . Solve this for  $y = 3$  gives  $x = -9, 11$  therefore  $(-9, 3)$  and  $(11, 3)$  are the points of intersection.

#### Exam-style Question: VCAA 2008 Spesh E2 A4

$P$  is any point on the hyperbola with equation  $x^2 - \frac{y^2}{4} = 1$ . If  $m$  is the gradient of any of the hyperbola at point  $P$ , then  $m$  could be.

The hyperbola has asymptotes  $\pm 2x$ , therefore the absolute value of gradient,  $|m| > 2$ . Therefore  $m \in (-\infty, -2) \cup (2, \infty) \equiv m \in \mathbb{R} \setminus [-2, 2]$ .

## 4 Functions

### 4.1 Tech

**Defining a function** Make sure you use `:=` to define functions! Alternatively, menu+1+1

#### 4.1.1 `fMax(rule,iv,lower,upper)` and `fMin(rule,iv,lower,upper)`

This finds the maximum and minimum values of a function over an interval. `iv` denotes the independent variable of the rule.

#### 4.1.2 tangentLine(rule,iv,x)

This finds the equation of the line tangent to the graph of the rule at the point with x-coordinate  $x$ . iv denotes the independent variable of the rule.

#### 4.1.3 normalLine(rule,iv,x)

This finds the equation of the normal line tangent to the graph of the rule at the point with x-coordinate  $x$ . iv denotes the independent variable of the rule.

#### 4.1.4 scriptedmath\poi(f(x),x)

Gives stationary points, axes intercepts, straight-line asymptotes, and endpoints.

#### 4.1.5 scriptedmath\inv(f(x),pointX)

Finds  $f^{-1}(x)$ . If the function is not one-to-one it will restrict domain to contain the point where  $x=pointX$ .

## 4.2 Average Value and Average Rate

**Average value** The average value of a continuous function  $f$  over  $[a, b]$  is given by:

$$f_{avg} = \frac{1}{b-a} \int_a^b f(x) dx$$

**Average rate of change** The average rate of change of a function  $f$  over  $[a, b]$  is given by:

$$A(x) = \frac{f(b) - f(a)}{b - a}$$

## 4.3 Transformations

$(x, y) \rightarrow (x + a, y)$	Translation $a$ units right
$(x, y) \rightarrow (x - a, y)$	Translation $a$ units left
$(x, y) \rightarrow (x, y + a)$	Translation $a$ units up
$(x, y) \rightarrow (x, y - a)$	Translation $a$ units down
$(x, y) \rightarrow (x, ay)$	Dilation from $x$ -axis by factor $a$
$(x, y) \rightarrow (ax, y)$	Dilation from $y$ -axis by factor $a$
$(x, y) \rightarrow (-x, y)$	Reflection in $y$ -axis
$(x, y) \rightarrow (x, -y)$	Reflection in $x$ -axis

### Exam-style Question: 2010 NEAP Methods E2 A12

The graph of  $f$  where  $f(x) = x^{-\frac{3}{2}}$  undergoes a dilation of factor 4 parallel to  $x$ -axis. The same result could be achieved had  $f$  undergone a dilation of factor:

- A)  $\frac{1}{8}$  from  $y$ -axis      B) 8 from  $y$ -axis      C)  $\frac{1}{8}$  from  $x$ -axis      D) 8 from the  $x$ -axis      E)  $\frac{1}{16}$  from the  $x$ -axis.

$$\begin{aligned} f\left(\frac{x}{4}\right) &= \left(\frac{x}{4}\right)^{-\frac{3}{2}} = 8x^{-\frac{3}{2}} \quad \text{As } \left(\frac{1}{4}\right)^{-\frac{3}{2}} = 8 \\ &= 8f(x) \implies \text{a factor of 8 from x-axis} \end{aligned}$$

## 4.4 Composite Functions

**Domain** The domain of a composite function  $f(g(x))$  is all the inputs  $x$  which are in the domain of  $g$  such that  $g(x) \in \text{dom } f$

## 4.5 Exponential Functions

### Exam-style Question: 2006 VCAA Methods E2 B3e

Find the values of  $k$ , where  $k \in \mathbb{R}^+$ , for which the equation  $3 - ke^x - e^{-x} = 0$  has one or more solutions for  $x$ .

Solving  $3 - ke^x - e^{-x} = 0$  for  $x$

Let  $u = e^x$

$$3 - ku - (u)^{-1} = 0 \equiv 3u - ku^2 - 1 = 0$$

$$u = \frac{-3 \pm \sqrt{9 - 4k}}{2k} = e^x \implies x = \ln\left(\frac{-3 \pm \sqrt{9 - 4k}}{2k}\right)$$

\* Argument of a logarithm must be real and positive

$$9 - 4k \geq 0 \implies k \leq \frac{9}{4}$$

$$\therefore 0 < k \leq \frac{9}{4} \because k \in \mathbb{R}^+$$

## 4.6 Simultaneous Unique Solutions

### Exam-style Question: 2007 VCAA Methods E2 A5

The simultaneous linear equations

$$mx + 12y = 24$$

$$3x + my = m$$

have a unique solution only for what values of  $m$ ?

Take the determinant of the 2x2 matrix of coefficients and solve for 0, this will give the values of  $m$  for which the gradients are equal (no solns or infinite solns).

$$\underline{m}x + \underline{12}y = 24$$

$$\underline{3}x + \underline{m}y = m$$

  $\det\begin{pmatrix} \underline{m} & \underline{12} \\ \underline{3} & \underline{m} \end{pmatrix} = m^2 - 36$

solve  $(m^2 - 36 = 0, m)$   $m = -6 \text{ or } m = 6$

**Exam-style Question: 2014 VCAA Methods E2 A17**

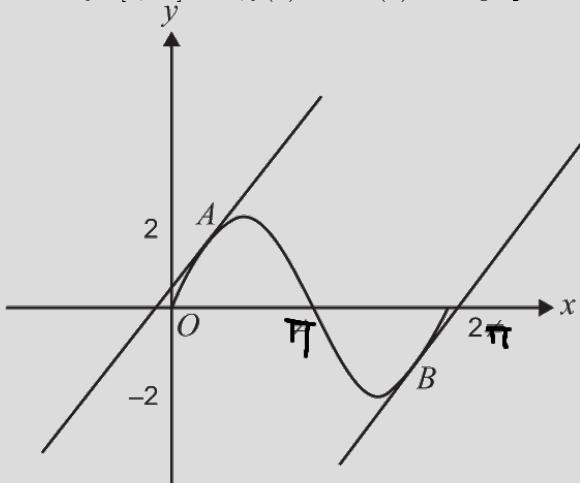
The simultaneous linear equations  $ax - 3y = 5$  and  $3x - ay = 8 - a$  have no solutions for what values of  $a$ ?

Take the determinant of the  $2 \times 2$  matrix of coefficients and solve for 0, then check each value it gives to see if lines are coincident or distinct parallel lines. In this case,  $a = 3$  produces coincidental lines, so  $a = -3$  is the only solution.

## 4.7 Tangents

**Exam-style Question: 2006 VCAA Methods E2 B1**

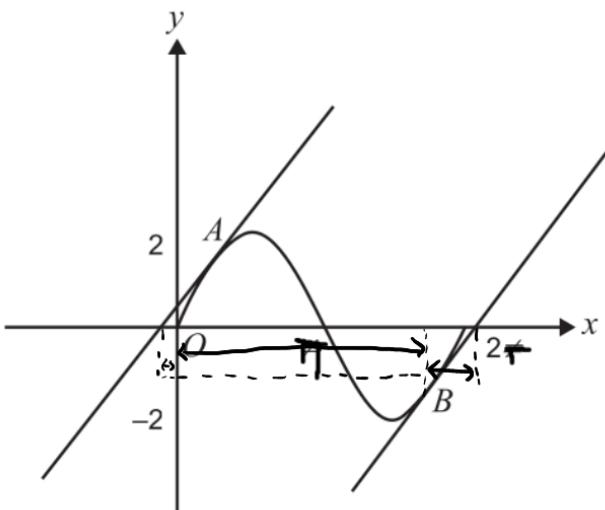
Consider  $f : [0, 2\pi] \rightarrow \mathbb{R}$ ,  $f(x) = 2 \sin(x)$ . The graph is shown below with tangents drawn at A and B.



The tangent to the curve at  $x = \frac{\pi}{3}$  is given by  $y = x + \frac{3\sqrt{3}-\pi}{3}$ .

The  $x$ -intercept of the tangent at A is  $\left(\frac{\pi-3\sqrt{3}}{3}, 0\right)$

The two tangents to the curve at points A and B have gradient 1. A translation of  $m$  units right in the positive  $x$  direction takes the tangent at A to the tangent at B. Find  $m$ .



Tangent at A cuts  $x$ -axis at  
 $x = \frac{\pi}{3} - \sqrt{3}$ .

Period of function is  $2\pi$

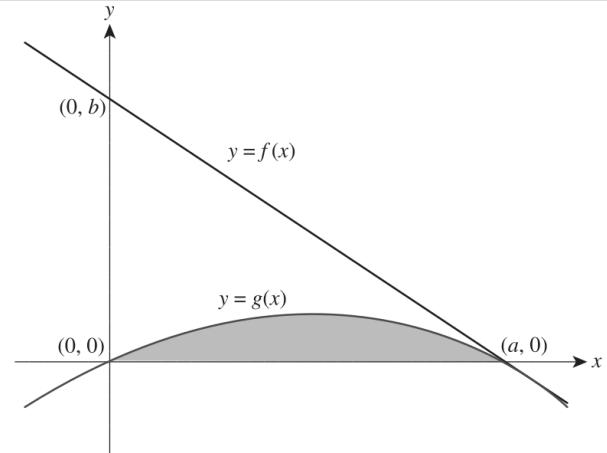
Tangent at B will be another  
 $\frac{\pi}{3} - \sqrt{3}$  units right after cycle  
 $\therefore m = 2\pi + 2\left(\frac{\pi-3\sqrt{3}}{3}\right)$

$$= \frac{4\pi}{3} + 2\sqrt{3}$$

## 4.8 Areas

**Exam-style Question: 2021 NEAP Methods MCQ20**

The graph below shows a linear function  $f$  and a quadratic function  $g$ , where  $f(x) \geq g(x)$  for  $x \in \mathbb{R}$



Given that  $f(a) = g(a)$  and  $f(x) = g(x)$  has one solution, the area of the shaded region in terms of  $a$  and  $b$  can be expressed as:

Maximum area occurs when parabola is tangential to the line at  $x = a$

$$g'(x) = k(2x - a) \rightarrow g'(a) = ak$$

$$\begin{aligned} m_{tangent} &= -\frac{b}{a} = g'(a) \\ ak &= \frac{-b}{a} \\ k &= -\frac{b}{a^2} \end{aligned}$$

$$\begin{aligned} \therefore g(x) &= -\frac{b}{a^2}x(x - a) \\ \text{max area} &= \int_0^a -\frac{b}{a^2}x(x - a)dx \\ &= \frac{ab}{6} \end{aligned}$$

## 5 Vectors and Kinematics

### 5.1 Vectors Tech

**Create a vector** `ctrl+(` creates a matrix which we can use for vectors.

#### 5.1.1 `norm(a)`

Menu+7+7+1 give the norm (magnitude) of a vector.

#### 5.1.2 `unitV(a)`

Menu+7+C+1 creates a unit vector in direction of a given vector.

#### 5.1.3 `dotP(a,b)`

Menu+7+C+3 gives the dot product of two vectors.

#### 5.1.4 `crossP(a,b)`

Menu+7+C+2 gives the cross product of two vectors.

### 5.1.5 sam\_vectors\vang(a,b)

gives the angle between two vectors.

### 5.1.6 sam\_vectors\vecres(a,b)

Put in vectors and it will find the vector resolute of  $a$  in both the direction of and perpendicular to  $b$ .

### 5.1.7 sam\_vectors\lindep(a,b,c,p)

Find a value for prounumeral  $p$  that makes the set of vectors  $a, b, c$  linearly dependent. In the first example below, we use it to find a value of  $p$  for which the vectors are linearly dependent. In the second example it is used to verify that a set of known vectors is linearly dependent. It returns a constant solution, so therefore they must be dependent.

$\text{lindep}([-1 \ 6 \ -3], [2 \ -8 \ 5], [3 \ 2 \ |1-p^2|], p)$

$$\begin{cases} p, p = \sqrt{5} \\ p, p = -\sqrt{5} \end{cases}$$

Done

$\text{lindep}([-1 \ 6 \ -3], [2 \ -8 \ 5], [3 \ 2 \ 4], x)$

$$\begin{cases} x, x = \mathbf{cI} \end{cases}$$

Done

## 5.2 Angles Between Vectors

### Exam-style Question: 2006 VCAA Spesh E2 B2

Point  $A$  has position vector  $\underline{a} = -\underline{i} - 4\underline{j}$ , point  $B$  has position vector  $\underline{b} = 2\underline{i} - 5\underline{j}$ , point  $C$  has position vector  $\underline{c} = 5\underline{i} - 4\underline{j}$  and point  $D$  has position vector  $\underline{d} = 2\underline{i} + 5\underline{j}$ . It is known that  $\cos(\angle ADC) = \frac{4}{5}$ . Find the cosine of  $\angle ABC$  and hence show that  $\angle ADC$  and  $\angle ABC$  are supplementary (add to  $\pi$ ).

$$\overrightarrow{BA} = -\underbrace{\underline{3i}}_{\sim} + \underbrace{\underline{j}}_{\sim} \quad \overrightarrow{BC} = \underbrace{\underline{3i}}_{\sim} + \underbrace{\underline{j}}_{\sim}$$

Let  $\theta = \angle ABC$

$$\begin{aligned} \cos \theta &= \frac{\overrightarrow{BA} \cdot \overrightarrow{BC}}{|\overrightarrow{BA}| |\overrightarrow{BC}|} \\ &= -\frac{4}{5} \end{aligned}$$

$$\arccos\left(-\frac{4}{5}\right) = \frac{\pi}{2} + \arcsin\left(\frac{4}{5}\right)$$

$$\begin{aligned} \therefore \arccos\left(-\frac{4}{5}\right) + \arccos\left(\frac{4}{5}\right) &= \frac{\pi}{2} + \arcsin\left(\frac{4}{5}\right) + \arccos\left(\frac{4}{5}\right) \\ &= \frac{\pi}{2} + \frac{\pi}{2} = \pi \end{aligned}$$

## 5.3 Linear Dependence

$$x_1 \underline{a_1} + x_2 \underline{a_2} + \dots + x_n \underline{a_n} = 0 \Rightarrow x_i = 0 \forall i \in [1, n]$$

A set of vectors is said to be linearly dependent if at least one of its members can be expressed as a linear combination of other vectors in the set. Alternatively, a set of vectors are linearly dependent if a vector could be removed from the set and not affect the set's span.

**Linear combination** A vector  $\underline{w}$  is a linear combination of  $\underline{u}$  and  $\underline{v}$  if it can be expressed in form  $\underline{w} = k_1\underline{u} + k_2\underline{v}$  for  $k_1, k_2 \in \mathbb{R}$ .

**General Case** A set  $S \in \mathbb{R}^n$  of  $n$  vectors  $\underline{a}_1, \underline{a}_2, \dots, \underline{a}_n$  is linearly dependent if and only if there exists  $k_1, k_2, \dots, k_n \in \mathbb{R}$  (not all equal 0) such that  $k_1\underline{a}_1 + k_2\underline{a}_2 + \dots + k_n\underline{a}_n = 0$

## 5.4 Scalar Product

The scalar product of vectors  $\underline{a}, \underline{b}$  is given by:

$$\underline{a} \cdot \underline{b} = |\underline{a}| |\underline{b}| \cos \theta$$

where  $\theta$  is the angle between the two vectors.

### Properties of the Scalar Product

$$\begin{aligned}\underline{a} \cdot \underline{b} &= \underline{b} \cdot \underline{a} \\ k(\underline{a} \cdot \underline{b}) &= (\underline{a} \cdot k\underline{b}) \\ \underline{a} \cdot (\underline{b} + \underline{c}) &= \underline{a} \cdot \underline{b} + \underline{a} \cdot \underline{c} \\ \underline{a} \cdot \underline{0} &= 0\end{aligned}$$

**Parallel Vectors** For parallel vectors  $\underline{a}, \underline{b}$

$$\underline{a} \cdot \underline{b} = \begin{cases} |\underline{a}| |\underline{b}| & \text{if } \underline{a}, \underline{b} \text{ are in the same direction} \\ -|\underline{a}| |\underline{b}| & \text{if } \underline{a}, \underline{b} \text{ are in opposite directions} \end{cases}$$

## 5.5 Vector and Scalar Resolutes

We can decompose a vector  $\underline{a}$  into the sum of two vectors in perpendicular directions.

**Vector Resolute in General** The Vector resolute of  $\underline{a}$  in direction  $\underline{b}$  is given by:

$$\underline{u} = \frac{\underline{a} \cdot \underline{b}}{\underline{b} \cdot \underline{b}} \underline{b} = \frac{\underline{a} \cdot \underline{b}}{|\underline{b}|^2} \underline{b} = \left( \underline{a} \cdot \frac{\underline{b}}{|\underline{b}|} \right) \left( \frac{\underline{b}}{|\underline{b}|} \right) = (\underline{a} \cdot \hat{\underline{b}}) \hat{\underline{b}}$$

**Scalar Resolute in General** The scalar resolute is the signed length of the vector resolute of  $\underline{a}$  in direction  $\underline{b}$

$$\underline{a} \cdot \hat{\underline{b}} = \frac{\underline{a} \cdot \underline{b}}{|\underline{b}|}$$

## 5.6 Vector Proofs

### 5.6.1 Collinearity

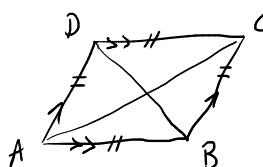
Three distinct points  $A, B, C$  are collinear if and only if  $\overrightarrow{AC} = k\overrightarrow{AB}$  for some  $k \in \mathbb{R} \setminus \{0\}$ .

### Miscellaneous Facts for Proof

**Parallel Vectors** For  $k \in \mathbb{R}^+$ , the vector  $k\underline{a}$  is in the same direction as  $\underline{a}$  and has magnitude  $k|\underline{a}|$  and the vector  $-k\underline{a}$  is in the opposite direction to  $\underline{a}$  and has magnitude  $k|\underline{a}|$ .

Two non-zero vectors  $\underline{a}$  and  $\underline{b}$  are parallel if and only if  $\underline{b} = k\underline{a}$  for some  $k \in \mathbb{R} \setminus \{0\}$ .

Prove that the diagonals of a rhombus are perpendicular using a vector method.

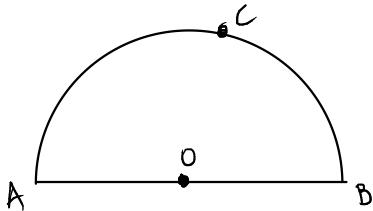


$$\begin{aligned} |\vec{AB}| &= |\vec{AD}| = |\vec{DC}| = |\vec{CB}| \\ \vec{AB} &= \vec{DC} \quad \text{and} \quad \vec{AD} = \vec{BC} \\ \vec{AC} \cdot \vec{BD} &= (\vec{AB} + \vec{BC}) \cdot (\vec{BC} + \vec{CD}) \\ &= (\vec{AB} + \vec{BC}) \cdot (\vec{BC} - \vec{AB}) \\ &= |\vec{BC}|^2 - |\vec{AB}|^2 \\ &= 0 \quad \text{by definition} \end{aligned}$$

$$\vec{AC} \cdot \vec{BD} = 0 \Leftrightarrow \vec{AC} \perp \vec{BD}$$

■

Prove that the angle subtended by a diameter at a point on a circle is a right angle.



Let  $O$  be the centre of the circle and let  $\vec{AB}$  be the diameter. Let  $C$  be a point on the circle's circumference other than  $A$  or  $B$ .

Let  $\underline{a} = \vec{OA}$ ,  $\underline{c} = \vec{OC}$ ,  $\vec{OB} = -\underline{a}$   $\Rightarrow |\vec{OA}| = |\vec{OB}| = |\vec{OC}| = r$  where  $r =$  radius of the circle.

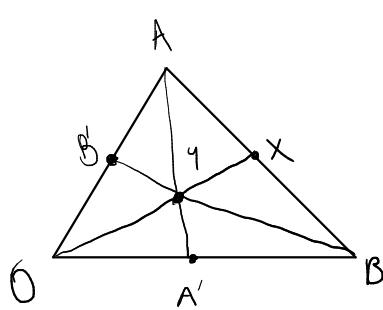
$$\vec{AC} = \vec{AO} + \vec{OC} = \underline{a} - \underline{a} \quad \text{and} \quad \vec{BC} = \vec{BO} + \vec{OC} = \underline{a} + \underline{c}$$

$$\begin{aligned} \vec{AC} \cdot \vec{BC} &= (\underline{a} - \underline{a}) \cdot (\underline{a} + \underline{c}) \\ &= |\underline{c}|^2 - |\underline{a}|^2 = r^2 - r^2 = 0 \quad \text{by definition} \end{aligned}$$

Hence  $\vec{AC} \perp \vec{BC} \Rightarrow \angle ACB$  is a right angle

■

Prove that the medians of a triangle are concurrent.



$$\text{Let } \underline{a} = \vec{OA}, \underline{b} = \vec{OB}$$

Show that  $|AY| : |YA'| = |BY| : |YB'| = 2 : 1$

$$\vec{AY} = \lambda \vec{AA}' \quad \vec{BY} = \mu \vec{BB}' \quad \text{for } \lambda, \mu \in \mathbb{R}$$

$$\vec{AA}' = \frac{1}{2} \underline{b} - \underline{a}$$

$$\vec{BB}' = -\underline{b} + \frac{1}{2} \underline{a}$$

$$\Rightarrow \vec{AY} = \lambda \left( \frac{1}{2} \underline{b} - \underline{a} \right)$$

$$\vec{BY} = \mu \left( \frac{1}{2} \underline{a} - \underline{b} \right)$$

$\vec{BY}$  can also be defined as:

$$\vec{BY} = \vec{BA} + \vec{AY} = -\underline{b} + \underline{a} + \lambda \left( \frac{1}{2} \underline{b} - \underline{a} \right) \quad \therefore -\mu \underline{b} + \frac{\mu}{2} \underline{a} = (1-\lambda) \underline{a} + \left( \frac{1}{2} - 1 \right) \underline{b}$$

Equating coefficients of independent vectors  $\underline{a}, \underline{b}$ :

$$\frac{\mu}{2} = 1 - \lambda \quad \textcircled{1} \quad -\mu = \frac{\lambda}{2} - 1 \quad \textcircled{2}$$

$$2 \times \textcircled{1} + \textcircled{2} : 0 = 2 - 2\lambda + \frac{\lambda}{2} - 1$$

$$1 = \frac{3}{2}\lambda$$

$$\lambda = \frac{2}{3}$$

$$\lambda = \frac{2}{3} \rightarrow \textcircled{1} \quad \text{gives } \mu = \frac{2}{3}$$

$$\therefore |\vec{AY}| : |\vec{YA}'| = |\vec{BY}| : |\vec{YB}'| = 2 : 1$$

By symmetry, the intersection of  $\vec{AA}'$  and  $\vec{OX}$  must also divide  $\vec{AA}'$  into a ratio of 2:1, and therefore this intersection is  $Y$ . Hence the three medians are concurrent at centroid  $Y$ .

■

## 5.7 Vector Equations

**Vector Equation of Line given by Point and Direction**  $\underline{r}(\lambda) = \underline{a} + \lambda \underline{d}, \lambda \in \mathbb{R}$ . Note that there is no unique vector equation for a given line  $\ell$ , as we can choose any point with position vector  $\underline{a}$  as our starting point and any vector  $\underline{d} \parallel \ell$ .

**Vector Equation of Line given by Two Points**  $\underline{r}(\lambda) = \underline{a} + \lambda (\underline{b} - \underline{a}), \lambda \in \mathbb{R}$  where  $\underline{a}$  and  $\underline{b}$  are the position vectors of the two points.

**Converting from Vector to Cartesian Equation** Consider the vector equation as a set of parametrics, where the coefficient of  $\underline{i}$  is equal to  $x$ , coefficient of  $\underline{j}$  is equal to  $y$ , etc. and then solving to get the cartesian form.

**Changing from Cartesian to Vector Equation** The direction vector of the line  $\underline{d}$  is given by  $\underline{d} = (\text{run})\underline{i} + (\text{rise})\underline{j}$ .

**Lines in 3D** Lines in three dimensions can be described in three ways, where  $\underline{a} = a_1\underline{i} + a_2\underline{j} + a_3\underline{k}$  is the position vector of a point A on the line and  $\underline{d} = d_1\underline{i} + d_2\underline{j} + d_3\underline{k}$  is a vector parallel to the line.

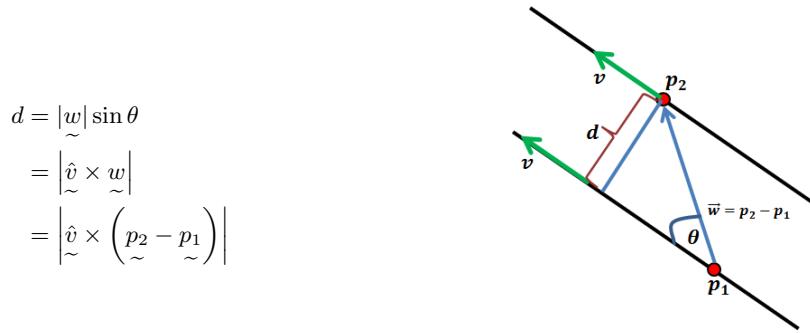
Vector	Parametric	Cartesian
$\underline{r}(\lambda) = \underline{a} + \lambda \underline{d}$	$x = a_1 + d_1 \lambda$ $y = a_2 + d_2 \lambda$ $z = a_3 + d_3 \lambda$	$\frac{x-a_1}{d_1} = \frac{y-a_2}{d_2} = \frac{z-a_3}{d_3}$

**Parallel and Perpendicular Lines** For two lines  $\ell_1 : \underline{r}_1(\lambda) = \underline{a}_1 + \lambda \underline{d}_1, \lambda \in \mathbb{R}$  and  $\ell_2 : \underline{r}_2(\gamma) = \underline{a}_2 + \gamma \underline{d}_2, \gamma \in \mathbb{R}$ :

- $\ell_1 \parallel \ell_2 \iff \underline{d}_1 \parallel \underline{d}_2$
- $\ell_1 \perp \ell_2 \iff \underline{d}_1 \perp \underline{d}_2 \iff \underline{d}_1 \cdot \underline{d}_2 = 0$

### Distance between two lines (non-parallel)

**Distance between two parallel lines** Let  $\underline{v}$  be the vector in the direction of the lines. Now let  $p_1$  be a point on line 1 and  $p_2$  be a point on line 2. The distance between the lines, as shown in the diagram below, can be calculated using the cross product.



## 5.8 Intersections and Skew Lines

### 5.8.1 Lines in 2D Space

A pair of lines in 2D space can

- intersect
- be parallel and distinct
- coincide

To check whether two parallel lines coincide choose a point on one line and see if it is on the other.

### 5.8.2 Lines in 3D Space

**Skew Lines** Two lines are skew lines if they are not parallel and do not intersect. Two lines are skew lines if and only if they do not lie in the same plane.

**Coincident and Parallel Lines** We can determine whether 3D lines are coincident or parallel and distinct by similar methods as in 2 dimensions. If parallel lines share a point they must coincide.

**Intersecting Lines** Two lines  $\ell_1 : \underline{r}_1(\lambda) = \underline{a}_1 + \lambda \underline{d}_1$  and  $\ell_2 : \underline{r}_2(\gamma) = \underline{a}_2 + \gamma \underline{d}_2$  have a common point if  $\exists \lambda, \gamma \in \mathbb{R} \ni \underline{r}_1(\lambda) = \underline{r}_2(\gamma)$ .

**Concurrence of 3 lines** A point of concurrence is where 3 or more lines meet.

**Angle Between 2 Lines** The angle between two lines can be found using the scalar product of their direction vectors. The angle is either  $\theta$  or  $\pi - \theta$ , whichever lies in the interval  $[0, \frac{\pi}{2}]$ .

## 5.9 Vector Product (Cross Product)

**Geometric Relationship** The relationship between the two vectors in a cross multiplication and the result is called 'mutually perpendicular'.

### Properties of the Vector Product

- Direction of  $\underline{a} \times \underline{b}$  is perpendicular to the plane containing  $\underline{a}$  and  $\underline{b}$ .
- $|\underline{a} \times \underline{b}| = |\underline{a}||\underline{b}| \sin \theta$
- $\underline{a} \parallel \underline{b} \implies |\underline{a} \times \underline{b}| = 0$
- $\underline{a} \perp \underline{b} \implies |\underline{a} \times \underline{b}| = |\underline{a}||\underline{b}|$
- Vector product is not associative  $(\underline{a} \times \underline{b}) \times \underline{c} \neq \underline{a} \times (\underline{b} \times \underline{c})$
- Vector product is not commutative  $\underline{a} \times \underline{b} \neq \underline{b} \times \underline{a}$
- Distributes over addition  $\underline{a} \times (\underline{b} + \underline{c}) = \underline{a} \times \underline{b} + \underline{a} \times \underline{c}$
- $\underline{a} \times \underline{b} = -(\underline{b} \times \underline{a})$

**Vector Product in Component Form** Let  $\underline{a} = a_1\hat{i} + a_2\hat{j} + a_3\hat{k}$  and  $\underline{b} = b_1\hat{i} + b_2\hat{j} + b_3\hat{k}$ , then:

$$\begin{aligned}\underline{a} \times \underline{b} &= \left( a_1\hat{i} + a_2\hat{j} + a_3\hat{k} \right) \times \left( b_1\hat{i} + b_2\hat{j} + b_3\hat{k} \right) \\ &= (a_2b_3 - a_3b_2)\hat{i} - (a_1b_3 - a_3b_1)\hat{j} + (a_1b_2 - a_2b_1)\hat{k}\end{aligned}$$

We can also use the determinant of a  $3 \times 3$  matrix to find the components of a vector product.

$$\underline{a} \times \underline{b} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \end{vmatrix} = \begin{vmatrix} a_2 & a_3 \\ b_2 & b_3 \end{vmatrix} \hat{i} - \begin{vmatrix} a_1 & a_3 \\ b_1 & b_3 \end{vmatrix} \hat{j} + \begin{vmatrix} a_1 & a_2 \\ b_1 & b_2 \end{vmatrix} \hat{k}$$

**Area from Vector Product**  $|\underline{a} \times \underline{b}|$  equals the area of the parallelogram spanned by  $\underline{a}$  and  $\underline{b}$

## 5.10 Vector Equations of Planes

**Equations of Planes** A plane  $\Pi$  can be described in 3-dimensional space with 2 vectors

- Position vector  $\underline{a}$  of a point on the plane
- A vector  $\underline{n}$  that is normal to the plane

Let  $\underline{r}$  be the position vector of a point  $P$  on the plane, then the vector  $\overrightarrow{AP} = \underline{r} - \underline{a}$  lies on the plane and therefore  $\overrightarrow{AP} \perp \underline{n}$ .

$$\begin{aligned}(\underline{r} - \underline{a}) \cdot \underline{n} &= 0 \\ \underline{r} \cdot \underline{n} - \underline{a} \cdot \underline{n} &= 0\end{aligned}$$

The above equation is known as the **vector equation** of the plane.

If we let  $\underline{r} = x\hat{i} + y\hat{j} + z\hat{k}$  and  $\underline{n} = n_1\hat{i} + n_2\hat{j} + n_3\hat{k}$  we can obtain the **cartesian equation** for the plane.

$$\begin{aligned}\underline{r} \cdot \underline{n} &= \underline{a} \cdot \underline{n} \\ n_1x + n_2y + n_3z &= k \text{ where } k = \underline{a} \cdot \underline{n}\end{aligned}$$

We can also describe planes with the use of parameters. For example, if  $n_1x + n_2y + n_3z = k$ , with  $n_3 \neq 0$  describes a plane, it can be described by the following parametrics:

$$x = \lambda \quad y = \gamma \quad z = \frac{k - n_1\lambda - n_2\gamma}{n_3} \quad \lambda, \gamma \in \mathbb{R}$$

We can determine the equations of planes with:

- a point on the plane and a normal vector at that point
- three points on the plane which are not collinear, or
- two lines on the plane that intersect

### Example: Equation of a Plane given Point and Normal Vector

A plane  $\Pi$  is such that the vector  $-\hat{i} + 5\hat{j} - 3\hat{k}$  is normal to it at point A with the position vector  $a = -3\hat{i} + 4\hat{j} + 6\hat{k}$  on the plane. Find the cartesian and vector equations that describe  $\Pi$ .

$$\begin{aligned} \underset{\sim}{r} \cdot \underset{\sim}{n} &= \underset{\sim}{a} \cdot \underset{\sim}{n} \\ \underset{\sim}{r} \cdot \left( -\hat{i} + 5\hat{j} - 3\hat{k} \right) &= \left( -3\hat{i} + 4\hat{j} + 6\hat{k} \right) \cdot \left( -\hat{i} + 5\hat{j} - 3\hat{k} \right) \\ \underset{\sim}{r} \cdot \left( -\hat{i} + 5\hat{j} - 3\hat{k} \right) &= 3 + 20 - 18 = 5 \\ \therefore \underset{\sim}{r} \cdot \left( -\hat{i} + 5\hat{j} - 3\hat{k} \right) &= 5 \end{aligned}$$

$$\begin{aligned} \underset{\sim}{r} &= x\hat{i} + y\hat{j} + z\hat{k} \\ \left( x\hat{i} + y\hat{j} + z\hat{k} \right) \cdot \left( -\hat{i} + 5\hat{j} - 3\hat{k} \right) &= 5 \\ -x + 5y - 3z &= 5 \end{aligned}$$

### Example: Equation of Plane Given 3 Points

Consider the plane containing the points  $A(0, 1, 1)$ ,  $B(2, 1, 0)$  and  $C(-2, 0, 3)$ . (a) Find cartesian equation of the plane.

$$\underset{\sim}{AB} = 2\hat{i} - \hat{k} \quad \text{and} \quad \underset{\sim}{AC} = -2\hat{i} - \hat{j} + 2\hat{k}$$

$$\begin{aligned} \underset{\sim}{AB} \times \underset{\sim}{AC} &= -\hat{i} - 2\hat{j} - 2\hat{k} \\ \therefore \underset{\sim}{n} &= -\hat{i} - 2\hat{j} - 2\hat{k} \end{aligned}$$

Use previous method to find plane equation to be:

$$-x - 2y - 2z = -4$$

(b) Find the axis intercepts of the plane

x-intercept: Let  $y = z = 0 \implies x = 4$

y-intercept: Let  $x = z = 0 \implies 2y = 4 \implies y = 2$

z-intercept: Let  $x = y = 0 \implies 2z = 4 \implies z = 2$

### Example: Equation of Plane Given 2 Intersecting Lines

Find a vector and cartesian equation of the plane containing the two lines:

$$\begin{aligned} \ell_1 : \underset{\sim}{r}_1(\lambda) &= 5\hat{i} + 2\hat{j} + \lambda \left( 2\hat{i} + \hat{j} + \hat{k} \right) \quad \text{and} \\ \ell_2 : \underset{\sim}{r}_2(\gamma) &= -3\hat{i} + 4\hat{j} + 6\hat{k} + \gamma \left( \hat{i} - \hat{j} - 2\hat{k} \right) \end{aligned}$$

$$\underset{\sim}{a} = \underset{\sim}{5\hat{i}} + \underset{\sim}{2\hat{j}} \text{ is on the plane}$$

Let  $\underset{\sim}{n}$  be the a vector perpendicular to both  $\underset{\sim}{d_1}$  and  $\underset{\sim}{d_2}$

$$\begin{aligned}\underset{\sim}{n} &= \underset{\sim}{d_2} \times \underset{\sim}{d_2} \\ &= -\underset{\sim}{\hat{i}} + \underset{\sim}{5\hat{j}} - \underset{\sim}{3\hat{k}}\end{aligned}$$

$$\begin{aligned}\therefore \underset{\sim}{r} \cdot \left( -\underset{\sim}{\hat{i}} + \underset{\sim}{5\hat{j}} - \underset{\sim}{3\hat{k}} \right) &= \underset{\sim}{a} \cdot \underset{\sim}{n} \\ &= -1 \times 5 + 2 \times 5 + -3 \times 0 \\ \therefore \underset{\sim}{r} \cdot \left( -\underset{\sim}{\hat{i}} + \underset{\sim}{5\hat{j}} - \underset{\sim}{3\hat{k}} \right) &= 5 \\ \implies -x + 5y - 3z &= 5\end{aligned}$$

## 5.11 Distances, Angles, Intersections of Planes

### 5.11.1 Distances

**Point to Plane distance** The distance from a point  $P$  to a plane  $\Pi$  is given by

$$d = \left| \overrightarrow{PQ} \cdot \hat{n} \right|$$

where  $Q$  is any point on the plane and  $\hat{n}$  is a unit vector normal to the plane

**Plane to Origin Distance** A plane that does not pass through the origin has a vector equation  $\underset{\sim}{r} \cdot \underset{\sim}{n} = k$  for  $k \neq 0$ . Take the point  $M$  as the closest point on the plane to the origin.  $\overrightarrow{OM} = m\underset{\sim}{n}$  where  $|m|$  is the distance of the plane to the origin.

$$\begin{aligned}\left( m\underset{\sim}{n} \right) \cdot \underset{\sim}{n} &= k \\ m(\underset{\sim}{n} \cdot \underset{\sim}{n}) &= m|\underset{\sim}{n}| = k \\ \therefore m &= \frac{k}{|\underset{\sim}{n}|}\end{aligned}$$

**Distance Between Parallel Planes** To find the distance between planes  $\Pi_1$  and  $\Pi_2$  we choose any point  $P$  on  $\Pi_1$  and find its nearest distance to  $\Pi_2$ , we can also use each plane's distance from origin.

### Example: Distance Between Parallel Planes

Consider the planes given by:

$$\Pi_1 : 2x - y + 2z = 5 \quad \Pi_2 : 2x - y + 2z = -2$$

Find the distance between the two planes.

First, we find the distance of each plane from the origin.

$$\underbrace{n}_{\sim} = \underbrace{2i - j + 2k}_{\sim} \implies |\underbrace{n}_{\sim}| = 3$$

$$\text{Signed distance from origin of } \Pi_1 = \frac{5}{|\underbrace{n}_{\sim}|} = \frac{5}{3}$$

$$\text{Signed distance from origin of } \Pi_2 = \frac{-2}{|\underbrace{n}_{\sim}|} = \frac{-2}{3}$$

$$\begin{aligned}\therefore \text{Distance between planes} &= \frac{5}{3} - \left( \frac{-2}{3} \right) \\ &= \frac{7}{3}\end{aligned}$$

**Distance Between Skew Lines** Given two skew lines it can be shown that there is a unique line segment  $PQ$  joining them that is perpendicular to both lines. Consider the lines defined by  $\underline{r}_1(\lambda) = \underline{a}_1 + \lambda \underline{d}_1$ ,  $\lambda \in \mathbb{R}$  and  $\underline{r}_2(\gamma) = \underline{a}_2 + \gamma \underline{d}_2$ ,  $\gamma \in \mathbb{R}$ . The distance between these skew lines is given by:

$$d = |(\underline{a}_2 - \underline{a}_1) \cdot \hat{\underline{n}}| \quad \hat{\underline{n}} = \frac{\underline{d}_1 \times \underline{d}_2}{|\underline{d}_1 \times \underline{d}_2|}$$

#### 5.11.2 Intersections and Angles

Two planes that are not parallel will intersect along a line. To find the angle between the planes choose a point  $P$  common to both planes and find the angle  $\theta$  between the normal vectors. The answer will either be  $\theta$  or  $\pi - \theta$ , whichever is in the interval  $[0, \frac{\pi}{2}]$ .

**Intersection of a Line and a Plane** The angle between a line and a plane is  $90^\circ - \theta$  where  $\theta$  is the angle between the line and a normal to the plane. To find the point of intersection between a plane and line, we need to find a value for  $t$  for which  $\underline{r}(t)$  represents a point on the line. That is,  $\underline{r}(t) \cdot \underline{n} = k$ . This will help us find a  $t$  value and then by subbing back in we find the point of intersection.

### Example: Intersection of Line and Plane

Consider the line represented by  $\underline{r}(\lambda) = 3\underline{i} - \underline{j} - \underline{k} + \lambda(\underline{i} + 2\underline{j} - \underline{k})$  and the plane represented by  $\underline{r} \cdot (\underline{i} + \underline{j} + 2\underline{k}) = 2$ . Find the point of intersection and angle of intersection between the line and plane.

#### Point of Intersection

$$\begin{aligned}\underline{r}(\lambda) \cdot (\underline{i} + \underline{j} + 2\underline{k}) &= 2 \\ \left( 3\underline{i} - \underline{j} - \underline{k} + \lambda \left( \underline{i} + 2\underline{j} - \underline{k} \right) \right) \cdot (\underline{i} + \underline{j} + 2\underline{k}) &= 2 \\ (3 + \lambda) + (-1 + 2\lambda) + 2(-1 - \lambda) &= 2 \\ \therefore \lambda &= 2 \\ \underline{r}(2) &= 5\underline{i} + 3\underline{j} - 3\underline{k}\end{aligned}$$

Therefore the point of intersection is  $(5, 3, -3)$ .

#### Angle of Intersection

$\underline{d} = \underline{i} + 2\underline{j} - \underline{k}$  is parallel to the line and  $\underline{n} = \underline{i} + \underline{j} + 2\underline{k}$  is normal to the plane.

$$\begin{aligned}\underline{d} \cdot \underline{n} &= |\underline{d}| |\underline{n}| \cos \theta \\ 1 &= 6 \cos \theta \\ \theta &= 80.4^\circ\end{aligned}$$

Therefore the angle of intersection is  $90^\circ - 80.4^\circ$  as  $80.4^\circ$  is the angle with the normal. Hence the angle of intersection is  $9.6^\circ$ .

#### 5.11.3 Intersection of Planes

**Example: Equation of the Line of Intersection**

Let  $\Pi_1$  and  $\Pi_2$  be planes represented by:

$$\Pi_1 : \underline{r} \cdot (\underline{i} + \underline{j} - 3\underline{k}) = 6 \quad \Pi_2 : \underline{r} \cdot (2\underline{i} - \underline{j} + \underline{k}) = 4$$

Find a vector equation to describe the line of intersection of these planes.

Consider the cartesian equations of two planes:

$$x + y - 3z = 6 \quad (1) \qquad 2x - y + z = 4 \quad (2)$$

$$(1) + (2) \rightarrow 3x - 2z = 10 \quad (3)$$

$$\text{Let } x = \lambda \implies z = \frac{3\lambda - 10}{2} \text{ (from (3))}, y = \frac{7\lambda - 18}{2} \text{ (from (2))}$$

This gives us the parametric equations for the line of intersection:

$$x = \lambda, y = \frac{7\lambda - 18}{2}, z = \frac{3\lambda - 10}{2}$$

Converting to vector form:

$$\underline{r}(\lambda) = -9\underline{j} - 5\underline{k} + \lambda \left( \underline{i} + \frac{7}{2}\underline{j} + \frac{3}{2}\underline{k} \right)$$

**5.12 Parametric Vector Equations****5.13 SUVAT and Constant Acceleration**

$$v = u + at \quad s = ut + \frac{1}{2}at^2 \quad v^2 = u^2 + 2as \quad s = \frac{1}{2}(u + v)t$$

**5.14 Terminal (Limiting) Velocity****Exam-style Question: VCAA 2017 Spesh E2 B2c**

After two seconds of falling, a skydiver's acceleration is affected by air resistance such that their acceleration is given by:

$$a = g - 0.01v^2$$

Find the limiting (terminal) velocity in  $ms^{-1}$  that they would reach.

$$\text{Let } a = 0$$

$$g = 0.01v^2$$

$$v = 10\sqrt{g}$$

**5.15 Velocity Functions of Time**

**Exam-style Question: VCAA 2007 Spesh E2 B5**

A car travelling at  $20\text{ms}^{-1}$  passes a stationary police car, and then decelerates so that its velocity  $v\text{ms}^{-1}$ , at time  $t$  seconds after passing the police car, is given by  $v = 20 - 2 \arctan(t)$ .

b) Explain why  $v$  will never equal 16.

$$\begin{aligned} t &\rightarrow \infty, \arctan(t) \rightarrow \frac{\pi}{2} \\ v &\rightarrow \left(20 - 2 \cdot \frac{\pi}{2}\right)^+ = (20 - \pi)^+ \\ v &> 20 - \pi > 16 \end{aligned}$$

## 5.16 Velocity-Time Graphs

**Displacement** is given by the signed area bounded by the graph and the  $t$ -axis.

**Acceleration** is given by the gradient.

**Distance** is given by the total area bounded by the graph and the  $t$ -axis.

## 5.17 Vector Functions

### 5.17.1 Describing Particle's Path

Consider  $\underline{r}(\lambda) = x(\lambda)\underline{i} + y(\lambda)\underline{j}, \lambda \in \mathbb{R}$ .  $\underline{r}(\lambda)$  represents a family of vectors defined by the parameter  $\lambda$ . Solve the components as normal parametrics to obtain the equation of the path.

### 5.17.2 Describing Curves with Vector Functions

Vector functions to describe curves are not unique.

## 5.18 Position Vectors as a Function of Time

Consider the vector function  $\underline{r}(t) = \cos(t)\underline{i} + \sin(t)\underline{j}, t \geq 0$ .

- At  $t = 0$ ,  $\underline{r}(t) = \underline{i}$  so the particle starts at  $(1, 0)$
- The particle moves at a constant speed along  $x^2 + y^2 = 1$
- The particle moves counterclockwise (sub in successive  $t$  values)
- The period of the motion is  $2\pi$ ; it takes  $2\pi$  units of time to complete one circle.

**Exam-style Question: 2019 MAV Spesh E2 QA13**

John is riding a jet ski. The ski is level with the pier (origin) and is travelling  $5\text{ms}^{-1}$  due North when John decides to accelerate uniformly. After accelerating for 40 seconds he is now travelling due East at  $4\text{ms}^{-1}$ . Given the unit vectors  $\underline{i}$  and  $\underline{j}$  are directed East and North respectively, find the position of the jet ski after the 40 second time period.

$$\begin{aligned} \underline{a} &= \frac{4\underline{i} - 5\underline{j}}{40} \\ \underline{r} &= 5\underline{i} \times 40 + \frac{1}{2} \left( \frac{4\underline{i} - 5\underline{j}}{40} \right) \times 40^2 \text{(Constant acceleration formula as acceleration is uniform)} \\ &= 80\underline{i} + 100\underline{j} \end{aligned}$$

## 5.19 Vector Calculus

### 5.19.1 Properties of Vector Derivatives

$$\begin{aligned}\frac{d}{dt}(\underline{c}) &= 0 \quad \text{For constant vector } \underline{c} & \frac{d}{dt}(k\underline{r}(t)) &= k \frac{d}{dt}(\underline{r}(t)), k \in \mathbb{R} \\ \frac{d}{dt}(\underline{r}_1(t) + \underline{r}_2(t)) &= \frac{d}{dt}(\underline{r}_1(t)) + \frac{d}{dt}(\underline{r}_2(t)) & \frac{d}{dt}(f(t) \cdot \underline{r}(t)) &= f(t) \frac{d}{dt}(\underline{r}(t)) + \underline{r}(t) \frac{d}{dt}(f(t)), f : \mathbb{D} \rightarrow \mathbb{R}\end{aligned}$$

### 5.19.2 Vector Antidifferentiation

Consider:

$$\int \underline{r}(\lambda) d\lambda = \int x(\lambda) \underline{i} + y(\lambda) \underline{j} + z(\lambda) \underline{k} d\lambda = \left( \int x(\lambda) d\lambda \right) \underline{i} + \left( \int y(\lambda) d\lambda \right) \underline{j} + \left( \int z(\lambda) d\lambda \right) \underline{k} = X(\lambda) \underline{i} + Y(\lambda) \underline{j} + Z(\lambda) \underline{k} + \underline{c}, \underline{c} \in \mathbb{R}^3$$

Where  $\frac{dX}{d\lambda} = x(\lambda)$  and  $\frac{dY}{d\lambda} = y(\lambda)$  and  $\frac{dZ}{d\lambda} = z(\lambda)$  and  $\underline{c}$  is a constant vector.

### 5.19.3 Velocity and Acceleration Along a Curve

Consider a particle with position vector  $\underline{r}(t) = x(t) \underline{i} + y(t) \underline{j}$ .

**Velocity**  $\underline{v} = \dot{\underline{r}}(t) = \dot{x}(t) \underline{i} + \dot{y}(t) \underline{j}$

**Acceleration**  $\underline{a}(t) = \ddot{\underline{r}}(t) = \ddot{x}(t) \underline{i} + \ddot{y}(t) \underline{j}$

**Distance Between Points on Vector Function Curve**  $|\underline{r}(t_1) - \underline{r}(t_0)|$

**Distance traversed along the curve** If  $\underline{r}(\lambda) = x(\lambda) \underline{i} + y(\lambda) \underline{j}$  describes the path of a particle, the distance traversed along the curve from  $\lambda = a$  to  $\lambda = b$  is given by:

$$\int_a^b \sqrt{\left( \frac{dx}{d\lambda} \right)^2 + \left( \frac{dy}{d\lambda} \right)^2} d\lambda$$

### 5.19.4 Alternative Forms of Acceleration

$$a = \frac{d^2x}{dt^2} = \frac{dv}{dt} = v \frac{dv}{dx} = \frac{d}{dx} \left( \frac{1}{2} v^2 \right)$$

#### Exam-style Question: 2015 MAV Spesh E2 A18

A body moves in a straight line such that its velocity is given by  $v = (1 - x)^2$  where  $x$  is the displacement from the origin. If the body starts at the origin, its acceleration after 2 seconds is?

$$a = V \frac{dV}{dx} = -2(1-x)^3$$

$$V = \frac{dx}{dt} = (1-x)^2 \Rightarrow t = \int \frac{1}{(1-x)^2} dx$$

$$t = \frac{1}{1-x} + c, c \in \mathbb{R}$$

$$x=0, t=0 \Rightarrow c=-1 \quad \therefore t = \frac{1}{1-x} - 1$$

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

$$\Rightarrow x = \frac{2}{3} \quad a = -2\left(1-\frac{2}{3}\right)^3 = \frac{-2}{27} \text{ m s}^{-2}$$

## 6 Complex Numbers

### 6.1 Tech

#### 6.1.1 Lines in the Complex Plane

Define  $z:=x+y\cdot i$ , then Menu+3+1 to get the solve() function and then input your complex relation, and solve for  $y$ .

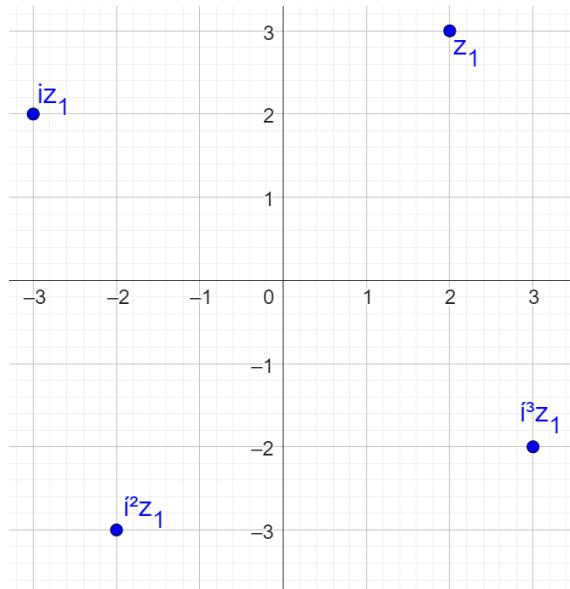
#### 6.1.2 Relations with Arguments in the Complex Plane

For relations in form  $\text{Arg}(z) = a$  we define  $z:=x+y\cdot i$ , and then use Menu+2+9+4 to input the angle() function. We then menu+3+1 solve(angle(z)=a,y) to get the relation.

### 6.2 Operations of Complex Numbers in Cartesian Form

For  $z_1 = a + bi$  and  $z_2 = c + di$  for  $a, b, c, d \in \mathbb{R}$

$$\begin{aligned} z_1 + z_2 &= (a+c) + (b+d)i & z_1 z_2 &= (ac - bd) + (ad + bc)i \\ z_1 - z_2 &= (a-c) + (b-d)i & kz &= ka + kbi \end{aligned}$$



**Multiplication by  $i$**   $z \times i, z \in \mathbb{C}$  gives a  $\frac{\pi}{2}$  rotation in the counterclockwise direction about the origin.

$$i^{4n} = 1 \quad i^{4n+1} = i \quad i^{4n+2} = -1 \quad i^{4n+3} = -i$$

### Exam-style Question: 2012 VCAA Spesh E2 QA6

For any complex number  $z$ , the location on an Argand diagram of the complex number  $i^3\bar{z}$  can be found by:

- A) Rotating  $z$  through  $\frac{3\pi}{2}$  counterclockwise about origin.
- B) Reflecting  $z$  about the  $x$ -axis and then reflecting about the  $y$ -axis.
- C) Reflecting  $z$  about the  $y$ -axis and then rotating anticlockwise through  $\frac{\pi}{2}$  about the origin.
- D) Reflecting  $z$  about the  $x$ -axis and then rotating anticlockwise through  $\frac{\pi}{2}$  about the origin.

$i^3\bar{z}$  is a reflection of  $z$  in the  $x$ -axis followed by a  $\frac{3\pi}{2}$  rotation anticlockwise about the origin. The result is the same as C.

## 6.3 Properties of Conjugates

For  $z = a + bi$ ,  $\bar{z} = a - bi$

$$z_1 \bar{z}_2 = \bar{z}_1 + \bar{z}_2 \quad z_1 \bar{z}_2 = \bar{z}_1 \bar{z}_2 \quad k\bar{z} = k\bar{z}, k \in \mathbb{R} \quad z\bar{z} = |z|^2 \quad z + \bar{z} = 2\operatorname{Re}(z)$$

**Multiplicative Inverse for Division** If  $z = a + bi \neq 0$  then

$$z^{-1} = \frac{a - bi}{a^2 + b^2} = \frac{\bar{z}}{|z|^2}$$

For division:

$$\frac{z_1}{z_2} = z_1 z_2^{-1} = \frac{z_1 \bar{z}_2}{|z_2|^2}$$

## 6.4 Polar Form Operations

**Conjugate**  $z = r \operatorname{cis} \theta \implies \bar{z} = r \operatorname{cis}(-\theta)$ . On an Argand diagram this can be represented as a reflection of  $z$  in the Real axis.

**Addition and Subtraction** You need to convert to cartesian form to complete these operations using  $\operatorname{cis} \theta = (\cos \theta + i \sin \theta)$ .

**Scalar Multiplication** If  $k \in \mathbb{R}^+$  then  $\operatorname{Arg}(z) = \operatorname{Arg}(kz)$ . If  $k \in \mathbb{R}^-$  then:

$$\operatorname{Arg}(kz) = \begin{cases} \operatorname{Arg}(z) - \pi & 0 < \operatorname{Arg}(z) \leq \pi \\ \operatorname{Arg}(z) + \pi & -\pi < \operatorname{Arg}(z) \leq 0 \end{cases}$$

**Complex Multiplication** Let  $z_1 = r_1 \operatorname{cis} \theta_1$  and  $z_2 = r_2 \operatorname{cis} \theta_2$

$$z_1 z_2 = r_1 r_2 \operatorname{cis}(\theta_1 + \theta_2) \quad \operatorname{Arg}(z_1 z_2) = \operatorname{Arg}(z_1) + \operatorname{Arg}(z_2) + 2k\pi, k \in \{-1, 0, 1\}$$

**Complex Division** Let  $z_1 = r_1 \operatorname{cis} \theta_1$  and  $z_2 = r_2 \operatorname{cis} \theta_2$ ,  $r_2 \neq 0$ .

$$\frac{z_1}{z_2} = \frac{r_1}{r_2} \operatorname{cis}(\theta_1 - \theta_2) \quad \operatorname{Arg}(z_1 z_2) = \operatorname{Arg}(z_1) - \operatorname{Arg}(z_2) + 2k\pi, k \in \{-1, 0, 1\}$$

$\operatorname{Arg}\left(\frac{1}{z}\right) = -\operatorname{Arg}(z)$  given  $z \notin \mathbb{R}^-$

## 6.5 Quadratics over Complex Numbers

**Sum of Squares** Since  $i^2 = -1$ , we can rewrite a sum of squares as a difference of squares using  $i$ .  $z^2 + a^2 = z^2 - (ai)^2 = (z + ai)(z - ai)$

## 6.6 Polynomials over Complex Numbers

**Remainder Theorem** Let  $\alpha \in \mathbb{C}$ . When a polynomial  $P(z)$  is divided by  $z - \alpha$ , the remainder is  $P(\alpha)$

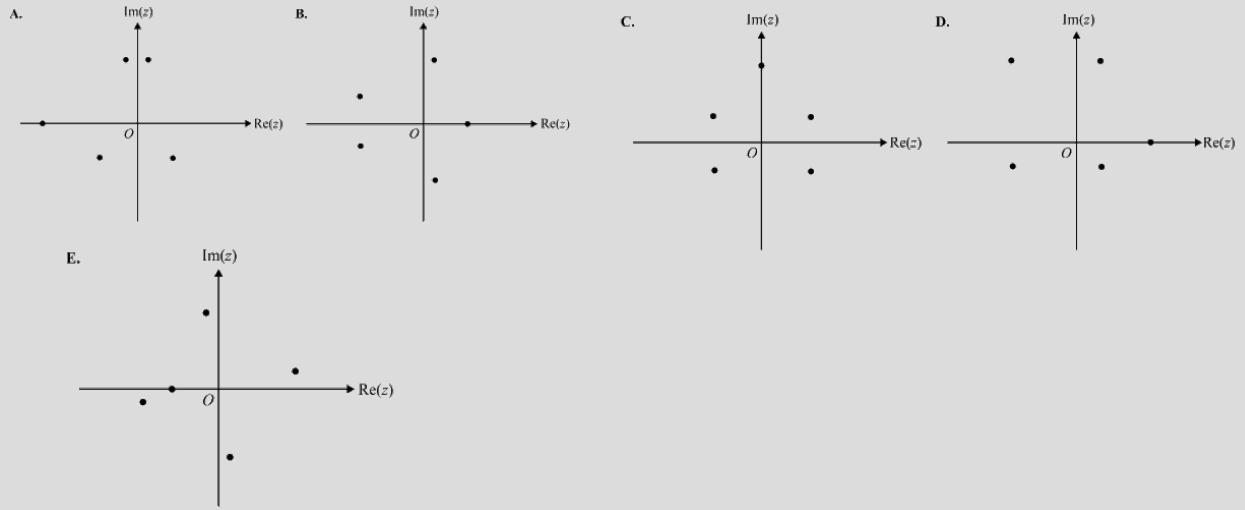
**Factor Theorem** Let  $\alpha \in \mathbb{C}$ . Then  $z - \alpha$  is a factor of  $P(z)$  if and only if  $P(\alpha) = 0$ .

**Conjugate Root Theorem** Let  $P(z)$  be a polynomial with real coefficients. If  $a + bi$  is a solution to  $P(z) = 0$ , with  $a, b \in \mathbb{R}$ , then the complex conjugate  $a - bi$  is also a solution.

**The Fundamental Theorem of Algebra** Every polynomial  $P(z) = a_n z^n + a_{n-1} z^{n-1} + \dots + a_1 z + a_0$  of degree  $n$ , where  $n \geq 1$  and the coefficients  $a_i$  are complex numbers, has at least one linear factor in the complex number system.

### Exam-style Question: VCAA 2007 Spesh E2 A6

Which one of the following diagrams would represent the roots of  $z^5, z^2 - z + c = 0$  in the complex plane for  $z \in \mathbb{C}$  and  $c \in \mathbb{R}$ ?



As the coefficients of  $z$  are all real numbers, therefore the roots will exist in conjugate pairs. Thus it is **B**.

## 6.7 Solving with De Moivre

Equations of form  $z^n = a, a \in \mathbb{C}$  can be solved with de Moivre's theorem.

### Example: de Moivre's theorem to solve basic case

Let  $z = r \operatorname{cis} \theta$  and  $a = q \operatorname{cis} \phi$ . Solve  $z^n = a$ .

$$z = r \operatorname{cis} \theta, a = q \operatorname{cis} \phi$$

$$z^n = a$$

$$r^n \operatorname{cis}(n\theta) = q \operatorname{cis} \phi$$

$$r = \sqrt[n]{q}$$

$$\operatorname{cis}(n\theta) = \operatorname{cis} \phi$$

$$n\theta = \phi + 2k\pi, k \in \mathbb{Z}$$

$$\theta = \frac{1}{n}(\phi + 2k\pi), k \in \mathbb{Z}$$

We then use the information to begin finding solutions.

### Complex Roots

- For  $n \in \mathbb{N}$  and  $a \in \mathbb{C}$ , the solutions  $z^n = a$  are called the  $n$ th-roots of  $a$
- Solutions lie evenly spaced on a circle about the origin of radius  $|a|^{\frac{1}{n}}$ .

- There are  $n$  solutions and they are spaced equally around the circle by intervals of  $\frac{2\pi}{n}$

**Roots of Unity** For  $n \in \mathbb{N}$  the solutions of  $z^n = 1$  are called the  $n$ th-roots of unity.

- Solutions lie on the unit circle
- There are  $n$  solutions and they are spaced evenly by  $\frac{2\pi}{n}$  around the circle
- $z = 1$  is always a solution

**Sum of the  $n$ th-roots of Unity**  $z^n = 1$  has a set of solutions defined by the geometric sequence with ratio  $w = \text{cis}(\frac{2\pi}{n})$ . The sum of the  $n$ th-roots of unity is always 0.

$$1, w, w^2, w^3, w^4, \dots, w^{n-1}, w = \text{cis}\left(\frac{2\pi}{n}\right), n \in \mathbb{N}$$

$$\sum_{i=0}^{n-1} w^i = 0 \text{ For } w = \text{cis}\left(\frac{2\pi}{n}\right), w^n = 1$$

## 6.8 Subsets of Complex Plane

### 6.8.1 Circles

A circle is defined as the set of points equidistant from a complex number.

For  $z, z_1 \in \mathbb{C}$  we can form a circle of radius  $r$  about  $z_1$  by:

$$(z - z_1)(\overline{z - z_1}) = r^2 \implies |z - z_1|^2 = r^2 \implies |z - z_1| = r$$

**Combination of Moduli** As  $|z| = |\bar{z}|$ , a linear combination of the moduli  $a|z| + b|\bar{z}| = r(a + b)$  will be a circle of radius  $r$ .

**Find Equation of Circle given Endpoints of Diameter** If  $z_1$  and  $z_2$  are the endpoints of the diameter of a circle, then the equation of a circle can be determined in **diametric form**:

$$(z - z_1)(\overline{z - z_2}) + (z - z_2)(\overline{z - z_1}) = 0$$

**Equation from Three Points** Given three complex numbers that lie on a circle, the centre  $z_0$  can be found by finding the intersection of the perpendicular bisectors of the points.

$$r = |z_0 - z_1| = |z_0 - z_2| = |z_0 - z_3| \quad z, z_1, z_2, z_3 \in \mathbb{C}$$

### 6.8.2 Lines

**Perpendicular Bisectors** The set of points equidistant on the complex plane from two complex numbers form a line.

$$|z - z_1| = |z - z_2| \quad z, z_1, z_2 \in \mathbb{C}$$

**Converting Perpendicular Bisector to Cartesian Form** First find midpoint of the line between  $z_1$  and  $z_2$ . Determine the slope between the points and take its negative reciprocal. Substitute in to  $y = m(x - x_1) + y_1$ .

#### Exam-style Question: VCAA Spesh 2017 E2 B4f

The equation of the line passing through the two roots of  $z^2 + 4z + 16 = 0, z \in \mathbb{C}$  can be expressed as  $|z - a| = |z - b|$ . Find  $b$  in terms of  $a$ .

$$\text{Let } a = \text{Re}(a) + \text{Im}(a)i \quad b = \text{Re}(b) + \text{Im}(b)i$$

$$\begin{aligned} \frac{\text{Re}(a) + \text{Re}(b)}{2} &= -2 & \text{Im}(b) &= \text{Im}(a) \\ \implies \frac{a+b}{2} &= -2 + \text{Im}(a)i \end{aligned}$$

$$\therefore b = -4 - a + 2\text{Im}(a)i = -4 - (\text{Re}(a) + \text{Im}(a)i) + 2\text{Im}(a)i = -4 - \text{Re}(a) - \text{Im}(a)i + 2\text{Im}(a)i$$

$$\therefore b = -4 - (\text{Re}(a) - \text{Im}(a)i) = -4 - \bar{a}$$

### 6.8.3 Rays

A ray extending at angle  $\theta$  from positive direction of the  $\operatorname{Re}(z)$  axis originating from  $z_1 \in \mathbb{C}$  is defined by:

$$\operatorname{Arg}(z - z_1) = \theta \quad z, z_1 \in \mathbb{C}, \theta \in (-\pi, \pi)$$

A ray is not defined for  $z = 0 + 0i$  as there is no unique angle for  $\operatorname{Arg}(0 + 0i)$

#### Exam-style Question: VCAA 2019 Spesh A5 (modified) - Intersections of Rays

Let  $z = x + yi$  for  $x, y \in \mathbb{R}$ . The rays  $\operatorname{Arg}(z - 2) = \frac{\pi}{4}$  and  $\operatorname{Arg}(z - (5 + i)) = \frac{5\pi}{6}$  for  $z \in \mathbb{C}$ , intersect at  $(a, b)$ . Find the value of  $b$ .

$$\operatorname{Arg}(z - 2) = \frac{\pi}{4} \implies y = x - 2, x > 2$$

$$\operatorname{Arg}(z - (5 + i)) = \frac{5\pi}{6} \implies y = \frac{-1}{\sqrt{3}}(x - 5) + 1, x < 5$$

Consider  $(a, b)$

$$\therefore b = a - 2 \quad b = \frac{-1}{\sqrt{3}}(a - 5) + 1$$

$$\therefore a = \sqrt{3} + 2, b = \sqrt{3}$$

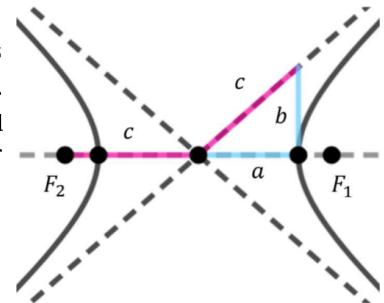
### 6.8.4 Hyperbolas

$$|z - z_1| - |z - z_2| = 2a \quad z, z_1, z_2 \in \mathbb{C}, a \in \mathbb{R}$$

$z_1, z_2$  are the foci of the ellipse, and  $a$  is the semi-major axis length.

**Find Cartesian Form** The centre of the hyperbola  $z_0$  is the midpoint of the foci, that is  $z_0 = \frac{z_1 + z_2}{2}$ . The linear eccentricity  $c$  of the hyperbola is given  $c = |z_0 - z_1| = |z_0 - z_2|$ . The semi-major axis length  $a$ , the semi-minor axis length  $b$  and eccentricity  $c$  are related by  $c^2 = a^2 + b^2 \implies b = \sqrt{c^2 - a^2}$ . We then use this to write a horizontal (left below) or vertical (right below) hyperbola.

$$\frac{(x - \operatorname{Re}(z_0))^2}{a^2} - \frac{(y - \operatorname{Im}(z_0))^2}{b^2} = 1 \quad \frac{(y - \operatorname{Im}(z_0))^2}{a^2} - \frac{(x - \operatorname{Re}(z_0))^2}{b^2} = 1$$



### 6.8.5 Intersections of Subsets

#### Exam-style Question: 2006 NEAP Spesh E2 A8

The values of  $\operatorname{Re}(z), z \in \mathbb{C}$  such that  $z$  belongs to  $S \cap T$  where  $S = \{z : |z - 1| \leq 1\}$  and  $T = \{z : \operatorname{Re}(z) + \operatorname{Im}(z) = 1\}$  are

Subset  $T$  represents a line with the equation  $x + y = 1$  or  $y = 1 - x$ . Subset  $S$  represents a circle with equation  $(x - 1)^2 + y^2 \leq 1$ . Substituting  $1 - x$  into the equation for  $S$  and solving in CAS gives  $1 - \frac{\sqrt{2}}{2} \leq x \leq \frac{\sqrt{2}}{2} + 1$

## 7 Logic and Proof

### 7.1 Converse, Negations, Contrapositives

For a conditional statement  $P \implies Q$ :

**Negation**  $P$  and  $\neg Q$

- de Morgan's Law**  $\neg(P \wedge Q) \equiv \neg P \vee \neg Q$
- $\neg(P \vee Q) \equiv \neg P \wedge \neg Q$
- $\neg(P \implies Q) \equiv P \wedge \neg Q$

**Converse**  $Q \implies P$

**Contrapositive**  $\neg Q \implies \neg P$

#### Exam-style Question: 2023 Heffernan Spesh E2 A1

Consider the following statement: 'If a number is a multiple of 6, then it is also a multiple of 3.' What is the **contrapositive** of this statement?

P is 'multiple of 6' and Q is 'multiple of 3'. The contrapositive is  $\neg Q \implies \neg P$ , which is 'if a number is not a multiple of 3 then it is not a multiple of 6.'

## 7.2 Proof of Equivalent Statements

To prove  $P \iff Q$  both  $P \implies Q$  and  $Q \implies P$  have to be shown to be true.

## 7.3 Proof by Contradiction

First, assume the statement is false, then show that this assumption leads to mathematical nonsense. Therefore we conclude that the assumption was wrong, and therefore the statement must be true.

## 7.4 Quantifiers and Counterexamples

$\forall$  : 'For all'       $\exists$  : 'There exists'

To prove universal statements ( $\forall$ ) we need to provide a general argument that holds for every case in the set. To disprove universal statements, we need to provide a counterexample where it does not hold.

To prove an existence statement ( $\exists$ ) we need to show that it holds for at least one member in the set. To disprove these statements, we prove that its negation is true.

### 7.4.1 Negations with Quantifiers

Recall de Morgan's laws, apply these as normal and then flip the quantifier symbol ( $\forall$  or  $\exists$ ).

## 7.5 Product and Sum Notation

$$\sum_{i=1}^n i^2 = 1^2 + 2^2 + \dots + n^2 \quad \prod_{i=1}^n (2i - 1) = 1 \times 3 \times 5 \times \dots \times (2n - 1)$$

## 7.6 Direct Proof

#### Exam-style Question: 1000 Spesh Questions Doc Proof 3

**Theorem.** There are no integers  $a$  and  $b$  such that  $4a + 8b = 34$ .

*Proof.*  $4a + 8b = 34 \implies 4(a + 2b) = 34$  and hence the statement is false as  $\nexists k \in \mathbb{Z} \ni 34 = 4k$  ■

## 7.7 Proof by Contradiction

To prove  $P \implies Q$  by contradiction, we suppose the negation of the statement  $\neg(P \implies Q)$  is true and show this results in nonsense.

#### Exam-style Question: 1000 Spesh Questions Doc Proof 2

**Theorem.**  $\sqrt{3} + \sqrt{7} < 2\sqrt{5}$

*Proof.* Suppose that  $\sqrt{3} + \sqrt{7} \geq 2\sqrt{5}$ . By squaring both sides we get  $3 + 2\sqrt{21} + 7 \geq 20$ .

$$\begin{aligned} 10 + 2\sqrt{21} &\geq 20 \\ \sqrt{21} &\geq 5 \\ 21 &\geq 25 \end{aligned}$$

$21 \geq 25$  is a contradiction, and thus  $\sqrt{3} + \sqrt{7} < 2\sqrt{5}$  ■

### Exam-style Question: 1000 Spesh Questions Doc Proof 43

**Theorem.**  $\cos \theta + \sin \theta \leq \sqrt{2}$

*Proof.* Suppose that  $\cos \theta + \sin \theta > \sqrt{2}$ .

$$\begin{aligned} (\cos \theta + \sin \theta)^2 &> 2 \\ \cos^2 \theta + 2 \cos \theta \sin \theta + \sin^2 \theta &> 2 \\ 1 + \sin 2\theta &> 2 \\ \sin 2\theta &> 1 \end{aligned}$$

As  $\sin 2\theta \in [-1, 1]$ , a contradiction has been reached, thus  $\cos \theta + \sin \theta \leq \sqrt{2}$ . ■

### Exam-style Question: 1000 Spesh Questions Doc Proof 51

**Theorem.** The square root of an irrational number  $m$  is also irrational.

*Proof.* Suppose that  $\sqrt{m} = \frac{a}{b}$      $a, b \in \mathbb{Z}$      $m \notin \mathbb{Q}$ .

$$b^2 m = a^2$$

The RHS is an integer, but LHS is not since  $m$  is by definition irrational. Hence a contradiction has been reached. Hence the square root of the irrational number  $m$  is also irrational. ■

## 7.8 Arithmetic Mean-Geometric Mean Inequality

For  $x, y \geq 0$ , the arithmetic mean is greater than or equal to the geometric mean.

$$\frac{x+y}{2} \geq \sqrt{xy}$$

### Example: AM-GM Inequality

**Theorem.** For  $a, b > 0$  and  $ab = 24$ , prove that  $2a + 3b \geq 24$ .

*Proof.* Assume  $ab = 24$ , using the AM-GM inequality we find:

$$\begin{aligned} 2a + 3b &= \frac{4a + 6b}{2} \\ &\geq \sqrt{(4a)(6b)} = \sqrt{24ab} \\ &= \sqrt{24 \times 24} \\ &= 24 \end{aligned}$$

$\therefore 2a + 3b \geq 24$  as required.



## 7.9 Proof by Induction

### Exam-style Question: University of Waikato Induction Problems Set Proof 18

**Theorem.**  $5^{2n+1} + 2^{2n+1} = 7k, k \in \mathbb{Z}$  for all integers  $n \geq 0$ .

*Proof.*  $\diamondsuit$  Hypothesis:

$$P(n) : 5^{2n+1} + 2^{2n+1} = 7k, k \in \mathbb{Z}$$

$\diamondsuit$  Base case:

$$P(0) : 5 + 2 = 7 = 7(1) \therefore \text{holds}$$

$\diamondsuit$  Inductive hypothesis:

Assume  $P(k)$  holds for all  $k \in \mathbb{Z}^+ \cup \{0\} : 5^{2k+1} + 2^{2k+1} = 7m, m \in \mathbb{Z}$

$\diamondsuit$  Inductive step:

$$P(k+1) : 5^{2k+3} + 2^{2k+3} = 7x, x \in \mathbb{Z}$$

$$\begin{aligned} LHS &= 5^2 \cdot 5^{2k+1} + 2^2 \cdot 2^{2k+1} = 25 \cdot 5^{2k+1} + 4 \cdot 2^{2k+1} = 4(5^{2k+1} + 2^{2k+1}) + 21 \cdot 5^{2k+1} \\ &= 4(7m) + 7(3 \cdot 5^{2k+1}) \\ &= 7(4m + 3 \cdot 5^{2k+1}) = 7x \end{aligned}$$

Therefore  $(\forall k \in \mathbb{Z}^+ \cup \{0\}) P(k) \implies P(k+1)$

By principle of mathematical induction,  $P(n)$  holds for  $n \geq 0$ .  $\blacksquare$

### Exam-style Question: 1000 Spesh Questions Doc Induction Proof 11

**Theorem.**  $\sum_{r=1}^n \frac{1}{(r+1)(r+2)} = \frac{n}{2(n+2)}$  for  $n \geq 1$

*Proof.*  $\diamondsuit$  Hypothesis:

$$P(n) : \sum_{r=1}^n \frac{1}{(r+1)(r+2)} = \frac{n}{2(n+2)}$$

$\diamondsuit$  Base case:

$$\begin{aligned} P(1) : \text{LHS} &= \sum_{r=1}^1 \frac{1}{(r+1)(r+2)} = \frac{1}{6} \\ \text{RHS} &= \frac{1}{2(1+2)} = \frac{1}{6} \end{aligned}$$

LHS=RHS  $\therefore P(1)$  holds

$\diamondsuit$  Inductive hypothesis:

Assume  $P(k)$  holds for all  $k \in \mathbb{Z} \cap [1, \infty) : \sum_{r=1}^k \frac{1}{(r+1)(r+2)} = \frac{k}{2(k+2)}$

◊ Inductive step:

$$P(k+1) : \sum_{r=1}^{k+1} \frac{1}{(r+1)(r+2)} = \frac{k+1}{2(k+3)}$$

$$\begin{aligned} \text{LHS} &= \sum_{r=1}^{k+1} \frac{1}{(r+1)(r+2)} = \sum_{r=1}^k \frac{1}{(r+1)(r+2)} + \frac{1}{(k+2)(k+3)} = \frac{k+1}{2(k+2)} + \frac{1}{(k+2)(k+3)} \\ &= \frac{1}{k+2} \left( \frac{k}{2} + \frac{1}{k+3} \right) \\ &= \frac{1}{2(k+2)} \left( \frac{k^2 + 3k + 1}{2(k+3)} \right) = \frac{1}{2(k+2)} \left( \frac{(k+1)(k+2)}{k+3} \right) \\ &= \frac{k+1}{2(k+3)} = \text{RHS} \end{aligned}$$

Therefore  $(\forall k \in \mathbb{Z} \cap [1, \infty)) P(k) \implies P(k+1)$  and therefore by the principle of mathematical induction,  $P(n)$  holds for all integers  $n \geq 1$ . ■

## 8 Circular Functions

### 8.1 Tech

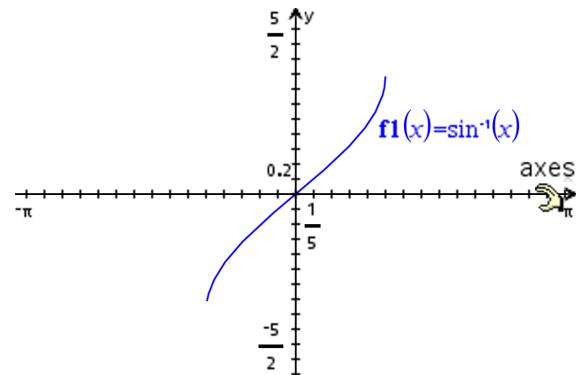
### 8.2 Inverse Circular Functions

Function	$\sin^{-1}$ or arcsin	$\cos^{-1}$ or arccos	$\tan^{-1}$ or arctan
Domain	$[-1, 1]$	$[-1, 1]$	$R$
Range	$\left[ -\frac{\pi}{2}, \frac{\pi}{2} \right]$	$[0, \pi]$	$\left( -\frac{\pi}{2}, \frac{\pi}{2} \right)$

**arcsin function** when  $y = \sin(x)$  is restricted to  $x \in [-\frac{\pi}{2}, \frac{\pi}{2}]$  the resulting function is one-to-one and therefore its inverse exists:

$$\arcsin : [-1, 1] \rightarrow \mathbb{R}, \arcsin(x) = y \quad \text{where} \quad \sin(y) = x, y \in \left[ -\frac{\pi}{2}, \frac{\pi}{2} \right]$$

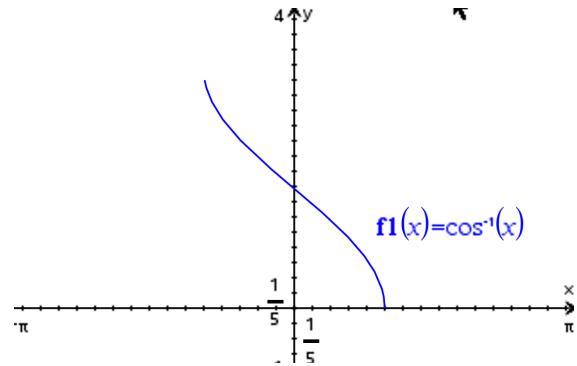
- domain of  $\arcsin(x)$ :  $x \in [-1, 1]$
- range of  $\arcsin(x)$ :  $y \in \left[ -\frac{\pi}{2}, \frac{\pi}{2} \right]$
- $\arcsin(\sin(x)) = x \forall x \in \left[ -\frac{\pi}{2}, \frac{\pi}{2} \right]$
- $\sin(\arcsin(x)) = x \forall x \in [-1, 1]$



**arccos function** when  $y = \cos(x)$  is restricted to  $x \in [0, \pi]$  the resulting function is one-to-one and therefore the inverse function exists.

$$\arccos : [-1, 1] \rightarrow \mathbb{R}, \arccos(x) = y \quad \text{where} \quad \cos(y) = x, y \in [0, \pi]$$

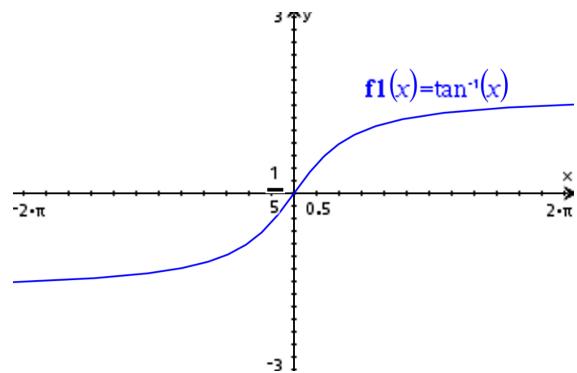
- domain of  $\arccos(x)$ :  $x \in [-1, 1]$
- range of  $\arccos(x)$ :  $y \in [0, \pi]$
- $\arccos(\cos(x)) = x \forall x \in [-1, 1]$
- $\cos(\arccos(x)) = x \forall x \in [0, \pi]$



**arctan function** when  $y = \tan(x)$  is restricted to  $x \in (-\frac{\pi}{2}, \frac{\pi}{2})$  the resulting function is one-to-one and therefore the inverse function exists.

$$\arctan : \mathbb{R} \rightarrow \mathbb{R}, \arctan(x) = y \quad \text{where} \quad \tan(y) = x, y \in \left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$$

- domain of  $\arctan(x)$ :  $x \in \mathbb{R}$
- range of  $\arctan(x)$ :  $y \in \left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$
- $\arctan(\tan(x)) = x \forall x \in \left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$
- $\tan(\arctan(x)) = x \forall x \in \mathbb{R}$



### Exam-style Question: 2007 NEAP Spesh E2 A7

The domain of  $f(x) = \sin(2x)$  is restricted so that it is one-to-one. The domain and range of the resulting inverse  $f^{-1}(x)$ , could be respectively:

The usual domain of  $\sin(x)$  for one-to-one is  $[-\frac{\pi}{2}, \frac{\pi}{2}]$ . The range of  $\sin(x)$  is  $[-1, 1]$ . The range is unchanged by the horizontal dilation, so the domain of  $f^{-1}(x)$  will be  $[-1, 1]$ . The domain of  $\sin(2x)$  to be one-to-one will halve, so it could be  $[-\frac{\pi}{4}, \frac{\pi}{4}]$ . Of the options,  $[\frac{3\pi}{4}, \frac{5\pi}{4}]$  is the only suitable option as it maintains the same period as  $[-\frac{\pi}{4}, \frac{\pi}{4}]$ . Therefore the range of the inverse will be  $[\frac{3\pi}{4}, \frac{5\pi}{4}]$ . Therefore C.

## 8.3 Symmetry Properties

### Sine

$$-\sin(\alpha) = \sin(2\pi - \alpha) \quad \sin(\pi - \alpha) = \sin(\alpha) \quad \sin\left(\alpha + \frac{\pi}{2}\right) = \cos(\alpha) \quad \sin\left(\alpha - \frac{\pi}{2}\right) = -\cos(\alpha)$$

### Cosine

$$-\cos(\alpha) = \cos(\pi - \alpha) \quad \cos(2\pi - \alpha) = \cos(\alpha) \quad \cos\left(\alpha - \frac{\pi}{2}\right) = \sin(\alpha) \quad \cos\left(\alpha + \frac{\pi}{2}\right) = -\sin(\alpha)$$

### Tangent

$$\tan\left(\alpha + \frac{\pi}{2}\right) = \tan\left(\alpha - \frac{\pi}{2}\right) - \cot(\alpha)$$

## 8.4 Solutions of Equations with Circular Functions

**Sine general solutions** For  $a \in [-1, 1]$  the general solution of  $\sin(x) = a$  is:

$$x = 2n\pi + \arcsin(a) \quad \text{or} \quad x = (2n+1)\pi - \arcsin(a), n \in \mathbb{Z}$$

**Cosine general solutions** For  $a \in [-1, 1]$  the general solution of  $\cos(x) = a$  is:

$$x = 2n\pi \pm \arccos(a), n \in \mathbb{Z}$$

**Tangent general solutions** For  $a \in \mathbb{R}$  the general solution of  $\tan(x) = a$  is:

$$x = n\pi + \arctan(a), n \in \mathbb{Z}$$

## 8.5 Product-to-sum identities

$$2\cos(x)\cos(y) = \cos(x-y) + \cos(x+y) \quad 2\sin(x)\sin(y) = \cos(x-y) - \cos(x+y) \quad 2\sin(x)\cos(y) = \sin(x+y) + \sin(x-y)$$

## 8.6 Sum-to-product identities

$$\begin{aligned} \cos(x) + \cos(y) &= 2\cos\left(\frac{x+y}{2}\right)\cos\left(\frac{x-y}{2}\right) & \cos(x) - \cos(y) &= -2\sin\left(\frac{x+y}{2}\right)\sin\left(\frac{x-y}{2}\right) \\ \sin(x) + \sin(y) &= 2\sin\left(\frac{x+y}{2}\right)\cos\left(\frac{x-y}{2}\right) & \sin(x) - \sin(y) &= 2\sin\left(\frac{x-y}{2}\right)\cos\left(\frac{x+y}{2}\right) \end{aligned}$$

# 9 Stats and Probability :skull:

## 9.1 Tech

### 9.1.1 `sam_prob\bpd(n,p,lower,upper)`

Outputs the probability distribution of a random binomial variable with  $n$  trials and probability of success  $p$  for a range of successes from lower to upper inclusive. It will also output the total probability of that range of successes.

### 9.1.2 `sam_prob\pdanal(x,px)`

Fill in the values from the discrete probability distribution where the set  $x$  is the row of  $x$  values and  $px$  is the row of  $\Pr(X=x)$  values. It will tell you the mean and variance of that distribution.

### 9.1.3 `scriptedmath\expec(f(x),x)`

Find the expected value of a continuous distribution with a density function  $f(x)$ .

### 9.1.4 `scriptedmath\var(f(x),x)`

Find the variance of a continuous distribution with a density function  $f(x)$ .

### 9.1.5 `scriptedmath\sd(f(x),x)`

Find the standard deviation of a continuous distribution with a density function  $f(x)$ .

### 9.1.6 `scriptedmath\mode(list,freqlist)`

Find the mode of list.

### 9.1.7 `scriptedmath\ns(eq,var)`

Finds a relation to describe the non-negative integer solutions for the variable var to the equation.

### 9.1.8 `normcdf(lower, upper, \mu, \sigma)`

Finds the area under a normal density curve over an interval. For  $\Pr(X \geq x)$  set the lower bound to be  $x$  and the upper bound to be  $\infty$ . For  $\Pr(X \leq x)$  set the upper bound to be  $x$  and the lower bound to be  $-\infty$ . Input  $\sigma$  and  $\mu$  as given in the question.

### 9.1.9 `invnorm(left tail prob, \mu, \sigma)`

Used for solving  $\Pr(X > x_c) = C$ . Input  $\text{invnorm}(1-C, \mu, \sigma)$  to get the value for  $x_c$ .

### 9.1.10 `binomcdf(n, p, lower, upper)`

Gives the  $\Pr(lower < X < upper)$  for  $X \sim \text{Bi}(n, p)$ .

### 9.1.11 `binompdf(n, p, x)`

Gives the  $\Pr(X = x)$  for  $X \sim \text{Bi}(n, p)$ .

### 9.1.12 `invbinomn(cumulative prob, prob, numsuccess)`

Menu+5+5+D. Inverse binomial with respect to  $N$  (number of trials). Given the probability of success on each trial (prob), and the number of successes (numsuccesses), this function returns the minimum number of trials,  $N$ , such that for  $X \sim \text{Bi}(N, prob)$ , that  $\Pr(X < N)$  is less than cumulative probability.

### 9.1.13 `sam_prob\normsum(x1,ltp1,x2,ltp2)`

Find the mean and standard deviation of a normal distribution given the left-tail probability of two values. Put in one of the values for  $x_1$  and its left-tail probability for  $ltp_1$ , and do the same for the second value.

### 9.1.14 Determine the Mean and Standard Deviation of a Normal Distribution

Suppose we have a normal distribution with mean 2 and unknown standard deviation, and we know that  $\Pr(X > 3) = 0.3$ . We first standardise to the standard normal random variable  $Z \sim N(0, 1^2)$ . Using the left tail area (in this case  $1-0.3=0.7$ ) to find the percentile on the standard normal distribution, then solve this for  $\frac{3-\mu}{\sigma}$  substituting appropriately to obtain the unknown standard deviation. The same process can be used for an unknown mean.

**Unknown Mean and Unknown Standard Deviation** Suppose  $X \sim N(\mu, \sigma^2)$ , but we know  $\Pr(X > 5) = 0.65$  and  $\Pr(X < 1) = 0.05$ . Observe the following:

$$\Pr(X > 5) = \Pr\left(Z > \frac{5-\mu}{\sigma}\right) = 0.65 \quad \text{and} \quad \Pr(X < 1) = \Pr\left(Z < \frac{1-\mu}{\sigma}\right) = 0.05$$

We can then use `invnorm()` to find the z-scores of each equation above, and set up an appropriate system of equations to solve.

$$\text{invnorm}(1 - 0.65, 0, 1) = \frac{5-\mu}{\sigma} \quad \text{and} \quad \text{invnorm}(0.05, 0, 1) = \frac{1-\mu}{\sigma}$$

### 9.1.15 Simulating Sample Means

`randNorm( $\mu$ ,  $\sigma$ ,  $n$ )` will give a list of  $n$  values randomly selected in a normal distribution of mean  $\mu$  and standard deviation  $\sigma$ . To find the sample mean apply `mean()` to this function.

To do this for  $m$  samples, add a **Lists and Spreadsheets** page in the CAS. In column A in the formula box input `seq(randNorm( $\mu, \sigma, n$ ), i, 1, m)`. Remember  $n$  is the sample size and  $m$  is the number of samples. Name the column `smeans`. Now add a **Data and Statistics** page and add `smeans` to the  $x$ -axis.

### 9.1.16 Confidence Interval (Spesh)

To quickly find a confidence interval, in a calculator window go to menu+6+6+1. Set input method to stats, then input the necessary values.

### 9.1.17 Determine a Confidence Interval (Methods)

Menu+6+6+5 inserts the 1-Prop z interval function. Input the number of successes  $x$ , the sample size  $n$ , and the confidence level  $C$ .

#### Exam-style Question: 2016 VCAA Methods B3g

A school has a class set of 22 new laptops kept in a recharging trolley. Provided each laptop is correctly plugged into the trolley after use, its battery recharges.

On a particular day, a class of 22 students uses the laptops. All laptop batteries are fully charged at the start of the lesson. Each student uses and returns exactly one laptop. The probability that a student does not correctly plug their laptop into the trolley at the end of the lesson is 10%. The correctness of any student's plugging-in is independent of any other student's correctness.

The laptop supplier finds that, in a particular sample of 100 laptops, six of them have a battery life of less than three hours.

Determine the 95% confidence interval for the supplier's estimate of the proportion of interest. Give the values correct to two decimal places.

menu+6+6+5 then input successes=6, n=100, C=0.95

### 9.1.18 Hypothesis Testing - One Tail

Menu+6+7+1 → zTest.  $\mu_0$  is the original population mean.  $\sigma$  is the general standard deviation (do not divide by  $\sqrt{n}$ ).  $\bar{x}$  is the sample mean.  $n$  is the sample size. Choose the type of alternative hypothesis and it will give you the necessary values.

**For two tail-tests:** Do the same as for a one tail test, but choose the  $\mu \neq \mu_0$  test type.

### 9.1.19 nSolve for brute force solving

In situations where `solve()` doesn't give a solution, even in approximate form, you can use `nsolve()` to brute force solve an equation.

### 9.1.20 Type II Error Probability

**Instances of one-tail tests** For a 5% significance one-tail hypothesis test, in order to calculate the probability of type II error use `invnorm(0.05,μ,σ/√n)` to get the value for the sample mean which determines the boundary between rejection and acceptance of  $H_0$ . From this, execute a `normcdf(ans,∞,true mean,σ/√n)` to find the probability of a Type II error.

**Instances of two-tail tests** For a 5% significance two-tail hypothesis test, in order to calculate the probability of type II error use `invnorm(0.025,μ,σ/√n)` to get the lower bound value for the 'acceptance region' and save this in a variable name like  $l$ . From this, do  $μ - l$  and save this as  $d$  then  $μ + d$  (save this as  $u$ ). Then execute `normcdf(l,u,true mean,σ/√n)` to find the probability of a Type II error.

## 9.2 Linear Functions of Random Variables

Consider a random variable  $Y$  which is a linear function of random variable  $X$

$$Y = aX + b \quad a, b \in \mathbb{R}$$

**Linear Functions of Discrete Random Variables** If  $X$  is a discrete random variable  $Y = aX + b$  is also a discrete random variable.

**Linear Functions of Continuous Random Variables** If  $X$  is a continuous random variable,  $Y = aX + b, a \neq 0$  is also a continuous random variable. For  $a > 0$ :

$$\begin{aligned} \Pr(Y \leq y) &= \Pr(aX + b \leq y) = \Pr\left(X \leq \frac{y-b}{a}\right) \\ \therefore \Pr(Y \leq y) &= \int_{-\infty}^{\frac{y-b}{a}} f(x)dx \end{aligned}$$

### Mean of Linear Functions of Random Variables

**Mean of Discrete Random Variables** For D.R.V's, the expected value  $E(X)$  of  $X$  gives:

$$E(X) = \sum_x x \cdot \Pr(X = x)$$

**Mean of Continuous Random Variables** For C.R.V's, the expected value  $E(X)$  of  $X$  gives:

$$E(X) = \int_{-\infty}^{\infty} x \cdot f(x)dx$$

For  $Y = aX + b$ :

$$E(Y) = E(aX + b) = aE(X) + b$$

**Variance of Linear Functions of Random Variables** Generally, for  $X$  is a random variable with variance  $\sigma^2$ , and  $Y = aX + b$  for  $a, b \in \mathbb{R}$ :

$$\begin{aligned} \text{Var}(Y) &= a^2 \text{Var}(X) = a^2 \sigma^2 \\ \text{s.d}(Y) &= \sqrt{a^2 \sigma^2} = |a| \sigma \end{aligned}$$

## 9.3 Independent Events

$$\text{Events } A, B \text{ are independent} \iff \Pr(A \cap B) = \Pr(A) \times \Pr(B) \quad \Pr(A|B) = \Pr(A)$$

## 9.4 Mutually Exclusive Events

Two events A and B are mutually exclusive:

$$\Pr(A \cap B) = 0 \quad \Pr(A \cup B) = \Pr(A) + \Pr(B)$$

## 9.5 Linear Combination of Random Variables

The idea of independent events also applies to random variables. If two random variables' joint probability function is the product of their individual probability functions, the random variables are said to be independent.

**aX vs X+X+X+...+X** Consider  $X$  representing the number that turns up on a dice roll. Then  $2X$  is the result of one dice roll, doubled.  $X + X$  is the equivalent of rolling the dice twice and adding the results.

$$\begin{aligned}\mathbb{E}(2X) &= \mathbb{E}(X + X) = 2\mathbb{E}(X) \\ \text{Var}(2X) &= 2^2\text{Var}(X) = 4\text{Var}(X) \quad \text{vs} \quad \text{Var}(X + X) = 1^2\text{Var}(X) + 1^2\text{Var}(X) = 2\text{Var}(X)\end{aligned}$$

**Sum of Identically Distributed Independent Random Variables** Variables with the same mean and standard deviation and are independent. The events predicted by the random variables are also independent, so therefore we can find the sum of probabilities by multiplying the individual probabilities. Consider  $X_1$  and  $X_2$  being discrete random variables for two dice rolling.

$$\Pr(X_1 + X_2 = 2) = \Pr(X_1 = 1, X_2 = 2) = \Pr(X_1 = 1) \times \Pr(X_2 = 1) = \frac{1}{6} \times \frac{1}{6} = \frac{1}{36}$$

**Exam-style Question: 2023 MAV Spec E2 QA20**

**Question 20**

At a particular fruit shop, the masses of apples are normally distributed with a mean of 80 g and a standard deviation of 5 g and the masses of mandarins are normally distributed with a mean of 60 g and a standard deviation of 8 g.

The masses of apples and mandarins are independent.

Let  $X$  represent the random variable which is the difference in the mean mass of a bag of four mandarins and the mean mass of a bag of three apples.

The mean and standard deviation respectively of  $X$  are

- A. 0,  $\sqrt{331}$
- B. 0,  $\sqrt{181}$
- C. 0,  $\sqrt{481}$
- D. 480,  $\sqrt{331}$
- E. 480,  $\sqrt{481}$

**Mean of Sum of n Identically Distributed Independent Random Variables**  $\mathbb{E}(X_1 + X_2 + \dots + X_n) = \mathbb{E}(X_1) + \mathbb{E}(X_2) + \dots + \mathbb{E}(X_n) = n\mu$

**Variance of Sum of n Identically Distributed Independent Random Variables**  $\text{Var}(X_1 + X_2 + \dots + X_n) = \text{Var}(X_1) + \text{Var}(X_2) + \dots + \text{Var}(X_n) = n\sigma^2$   
 $\text{sd}(X_1 + X_2 + \dots + X_n) = \sqrt{\text{Var}(X_1 + X_2 + \dots + X_n)} = \sqrt{n}\sigma$

**Linear Combinations of n Independent Random Variables** A random variable  $Y$  which is a linear combination of random variables  $X_1, X_2, \dots, X_n$  is given by  $Y = a_1X_1 + a_2X_2 + \dots + a_nX_n$  for  $a_1, a_2, \dots, a_n \in \mathbb{R}$ .

$$\mathbb{E}(a_1X_1 + a_2X_2 + \dots + a_nX_n) = a_1\mathbb{E}(X_1) + a_2\mathbb{E}(X_2) + \dots + a_n\mathbb{E}(X_n)$$

$$\text{Var}(a_1X_1 + a_2X_2 + \dots + a_nX_n) = a_1^2\text{Var}(X_1) + a_2^2\text{Var}(X_2) + \dots + a_n^2\text{Var}(X_n)$$

$$\text{sd}(a_1X_1 + a_2X_2 + \dots + a_nX_n) = \sqrt{a_1^2\text{Var}(X_1) + a_2^2\text{Var}(X_2) + \dots + a_n^2\text{Var}(X_n)}$$

**Linear Combinations of Normal Random Variables** A linear combination of normally distributed random variables is also a normally distributed random variable.

## 9.6 Discrete Probability

**Exam-style Question: 2021 NEAP Methods MCQ 9**

A discrete random variable  $X$  has the following probability distribution, where  $k$  and  $m$  are real constants.

$x$	0	1	2	3
$\Pr(X = x)$	$m$	$k$	$k - \frac{1}{4}$	$k^2$

The maximum value of  $m$  is:

$$\begin{aligned} 0 \leq \Pr(X = 2) \leq 1 &\implies 0 \leq k - \frac{1}{4} \leq 1 \\ \therefore k_{\min} &= \frac{1}{4} \\ m &= 1 - \left( \frac{1}{4} + 0 + \frac{1}{4} \right) \\ &= \frac{11}{16} \end{aligned}$$

**Exam-style Question: 2016 VCAA Methods MCQ 19**

Consider the discrete probability distribution with random variable  $X$  below:

$x$	-1	0	$b$	$2b$	4
$\Pr(X = x)$	$a$	$b$	$b$	$2b$	0.2

The smallest and largest possible values of  $\mathbb{E}(X)$  are:

$$\begin{aligned} \mathbb{E}(X) &= -a + b^2 + 4b^2 + 0.8 = 0.8 + 5b^2 - a \\ a + 4b + 0.2 &= 1 \rightarrow a + 4b = 0.8 \\ \mathbb{E}(X) &= 0.8 + 5b^2 - (0.8 - 4b) = 5b^2 + 4b = b(4 + 5b) \\ &\text{Parabola with intercept } b = 0, b > 0 \\ \therefore \mathbb{E}_{\min}(X) &= 0 \\ 0 \leq a \leq 0.8 &\rightarrow 0 \leq 0.8 - 4b \leq 0.8 \\ \implies -0.8 &\leq -4b \leq 0 \rightarrow 0.2 \geq b \geq 0 \\ &\text{Taking maximum value of } b: b = 0.2 \\ \therefore \mathbb{E}_{\max}(X) &= 0.2 \cdot (4 + 5 \cdot 0.2) = 1 \end{aligned}$$

## 9.7 Normal Probability

$$X \sim N(\mu, \sigma^2)$$

**Symmetry Properties of Normally Distributed Probabilities** Consider  $Z \sim N(0, 1)$ .

- $\Pr(Z > a) = 1 - \Pr(Z \leq a)$
- $\Pr(Z < -a) = \Pr(Z > a)$
- $\Pr(-a < Z < a) = 1 - 2\Pr(Z \geq a) = 1 - 2\Pr(Z \leq -a)$

**Exam-style Question: 2010 NEAP Methods E2 B3**

A winery produces bottles of wine in two sizes: standard and large. For each size, the content of the bottles are normally distributed according to the following:

Bottle Size	Mean	Standard Deviation
standard	0.760	0.008
large	$\mu$	$\sigma$

The probability that a randomly selected standard bottle contains fewer than 0.750 litres of wine is known to be 0.1056. Of the large bottles, 8% contain more than 1.023 litres and 4% contain less than 0.994 litres. Show that the mean and standard deviation of the large bottles can be found by solving the system of equations:  $\mu + 1.4051\sigma = 1.023$  and  $\mu - 1.7507\sigma = 0.994$ .

$$X \sim N(\mu, \sigma^2) \quad \Pr(X > 1.023) = 0.08 \quad \Pr(X < 0.994) = 0.04$$

$$Z \sim N(0, 1)$$

$$\Pr(X > 1.023) = \Pr\left(Z > \frac{1.023 - \mu}{\sigma}\right) = 0.08 \quad \text{invnorm}(0.92, 0, 1) \text{ gives } \frac{1.023 - \mu}{\sigma} = 1.4051 \text{ standard deviations}$$

$$\Pr(X < 0.994) = \Pr\left(Z < \frac{0.994 - \mu}{\sigma}\right) = 0.04 \quad \text{invnorm}(0.04, 0, 1) \text{ gives } \frac{0.994 - \mu}{\sigma} = -1.7507 \text{ standard deviations}$$

$$\therefore \mu + 1.4051\sigma = 1.023$$

$$\mu - 1.7507\sigma = 0.994 \text{ as required}$$

**Question 3**

The Bouncy Ball Company (BBC) makes tennis balls whose diameters are normally distributed with mean 67 mm and standard deviation 1 mm. The tennis balls are packed and sold in cylindrical tins that each hold four balls. A tennis ball fits into such a tin if the diameter of the ball is less than 68.5 mm.

- a. What is the probability, correct to four decimal places, that a randomly selected tennis ball produced by BBC fits into a tin?

$$D \sim N(67, 1)$$

$$\Pr(D < 68.5) = 0.9332$$

\*normcdf(-∞, 68.5, 67, 1)



2 marks

BBC management would like each ball produced to have diameter between 65.6 and 68.4 mm.

- b. What is the probability, correct to four decimal places, that the diameter of a randomly selected tennis ball made by BBC is in this range?

$$D \sim N(67, 1)$$

$$\Pr(65.6 < D < 68.4) = 0.8385$$

\*normcdf(65.6, 68.4, 67, 1)

2 marks

- c. i. What is the probability, correct to four decimal places, that the diameter of a tennis ball which fits into a tin is between 65.6 and 68.4 mm?

$$D \sim N(67, 1)$$

$$\Pr(65.6 < D < 68.4 | D < 68.5) = \Pr(65.6 < D < 68.4) \quad * \text{part b}$$

$$\Pr(D < 68.5) \quad * \text{part a}$$

$$= 0.8985 \checkmark$$

- ii. A tin of four balls is selected at random. What is the probability, correct to four decimal places, that at least one of these balls has diameter outside the desired range of 65.6 to 68.4 mm?

$$X \sim Bi(4, 1 - 0.8985) \quad * \text{do not use rounded value from i}$$

$$\Pr(X \geq 1) = 0.3482 \checkmark \quad * \text{binomcdf}(t, 1 - 0.8985, 1, 4)$$

(1+2=3 marks)

BBC management wants engineers to change the manufacturing process so that 99% of all balls produced have diameter between 65.6 and 68.4 mm. The mean is to stay at 67 mm but the standard deviation is to be changed.

- d. What should the new standard deviation be (correct to two decimal places)?

$$D \sim N(67, \sigma) \quad Z \sim N(0, 1)$$

$$\Pr(D < 68.4) = 0.995$$

$$\Pr\left(Z < \frac{68.4 - 67}{\sigma}\right) = 0.995 \quad * \text{typical standardisation}$$

$$\frac{68.4 - 67}{\sigma} = 2.5758$$

$$\sigma = 0.54 \text{ mm} \checkmark$$

invNorm(0.995, 0, 1)

2.575829303

(3 marks)

BBC sells tennis balls directly to tennis clubs once a year. If a tennis club buys its balls from BBC one year, there is an 80% chance it will buy its balls from BBC the next year. If a tennis club does not buy its balls from BBC one year, there is a 15% chance it will buy its balls from BBC the next year.

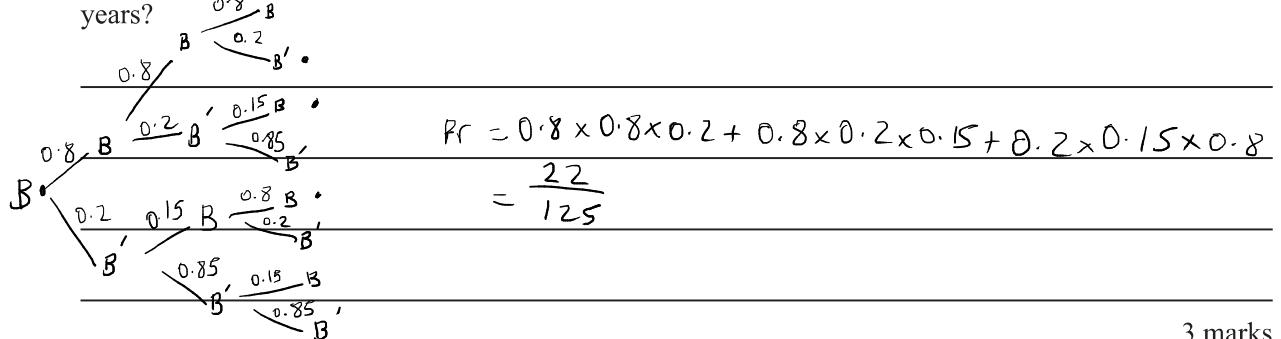
Suppose the Melbourne Tennis Club buys its tennis balls from BBC this year.

- e. What is the exact probability that it will buy its tennis balls from BBC for the next three years?

$$\text{Pr}(\text{buys for next three years}) = (0.8)^3 = \frac{64}{125} \checkmark$$

2 marks

- f. What is the exact probability that it will buy its tennis balls from BBC for exactly two of the next three years?



3 marks

Let  $p$  be the probability that the Melbourne Tennis Club will buy its tennis balls from BBC  $n$  years after 2009 given that it buys them from BBC in 2009.

- g. Find the smallest value of  $n$  such that  $p \leq 0.45$ .

OLD SD

2 marks

Total 17 marks

## 9.8 The Binomial Distribution

**Bernoulli Sequence** describes a sequence of trials for which there are two possible outcomes (success, failure), the probability of success  $p$  is constant for all trials, and the trials are independent. The number of successes in a Bernoulli sequence of  $n$  trials is called a Binomial Random Variable denoted  $X \sim Bi(n, p)$

### Exam-style Question: Suzanne Cory 2018 SAC3 Part II Q2e/f

In an isolated incident, Ricardo got his CAS stolen when he left it unattended in a breakout room in the G16-21 area after school one day. He found it later being sold on Gumtree.

Chelsea, from his homegroup, thinks she saw who walked into the breakout room. However, she was sitting quite far away, and her accusations are flimsy at best. To verify her claim, Mr. Mott tested her eyesight, by assessing her ability to identify a student from the claimed distance away.

The probability that she would correctly identify a student is 0.8. In the test to identify 8 students from distance,  $B$  is the random variable following a binomial distribution for the number of students she identifies correctly.

- e) What is the probability she identified exactly 7 students correctly, given that she correctly identified the first two (give your answer to 4dp).

We know  $B \sim Bi(8, 0.8)$  We know the outcomes of two out of eight trials, both being successes. So we can treat this as a binomial variable  $B_1 \sim Bi(2, 0.8)$ , we then treat the remaining 6 trials as a binomial variable  $B_2 \sim Bi(6, 0.8)$ .

$$\Pr(B = 7 | \text{first two are correct}) = \Pr(B_2 = 5 | B_1 = 2) = \frac{\Pr(B_2 = 5) \times \Pr(B_1 = 2)}{\Pr(B_1 = 2)}$$

$$\frac{\Pr(B_2 = 5) \times \Pr(B_1 = 2)}{\Pr(B_1 = 2)} = \Pr(B_2 = 5) = 0.3932 \quad \text{binompdf}(6, 0.8, 5)$$

- f) What is the minimum number of students in the test to ensure that the probability of Chelsea identifying at least 7 of them is 0.46?

$$\begin{aligned} X &\sim Bi(n, 0.8) \\ \Pr(X \geq 7) &\geq 0.46 \\ \implies \Pr(X \leq 6) &\leq 0.54 \\ \implies n = 8 & \quad \text{invBinomN}(0.54, 0.8, 6) \end{aligned}$$

### 9.8.1 Inverse Binomial

### Exam-style Question: 2008 VCAA Methods MCQ 5

Let  $X$  be a discrete random variable with a binomial distribution. The mean of  $X$  is 1.2 and the variance of  $X$  is 0.72. The values of  $n$  (the number of independent trials) and  $p$  (the probability of success in one trial) are:

$$\mu = np = 1.2$$

$$\sigma^2 = np(1 - p)$$

Solving the system gives  $n = 3, p = 0.4$

**Exam-style Question: 2022 VCAA NHT Methods QB4f**

The proportion of custard doughnuts as a proportion of all doughnuts made in the bakery is 0.44. Find the minimum number of doughnuts required in a box to ensure that the probability of having at least 12 custard doughnuts in a box is greater than 90%.

`invBinomN(0.1,0.44,11)` gives 35, the minimum number of doughnuts. Cumulative probability is  $1-0.9=0.1$ . Probability of success if the proportion, and the number of successes is one less than the threshold (12).

## 9.9 Sample Means

### Populations and samples

- **Population** is the set of all eligible members of the intended group of study.
- **Sample** is a subset of the population which is selected to make inferences about the population.
- The **population mean**  $\mu$  is the mean of all values of a measure in the entire population.
- The **sample mean**  $\bar{x}$  is the mean of the values of measure in a particular sample. Since this varies based on the contents of a random sample, we consider  $\bar{x}$  as being values of a random variable  $\bar{X}$

**Sample Mean of a normal random variable** Let  $X$  be a normally distributed random variable with mean  $\mu$  and standard deviation  $\sigma$ . Let  $X_1, X_2, \dots, X_n$  represent a sample size of  $n$  selected from this population. The sample mean is defined as:

$$\bar{X} = \frac{X_1 + X_2 + \dots + X_n}{n}$$

The sample mean  $\bar{X}$  is normally distributed with  $E(\bar{X}) = \mu$  and  $sd(\bar{X}) = \frac{\sigma}{\sqrt{n}}$ .

**Example: Edrolo Sample Mean MCQ**

The diameter, in metres, of trees in a certain forest is distributed with the following density function:

$$g(x) = \frac{12}{2401}(x-3)(x-10)^2, 3 \leq x \leq 10$$

Find the probability that the mean diameter of a sample of 40 trees is less than 6m to 2 decimal places.

Let  $G$  be the random variable representing the diameter of a randomly selected tree. The sample size is large enough that the distribution of sample means will be approximately normal.

$$E(G) = \int_3^{10} x \times \frac{12}{2401}(x-3)(x-10)^2 dx = \frac{29}{5}$$

$$Var(G) = E(G^2) - [E(G)]^2 = \int_3^{10} x^2 \times \frac{12}{2401}(x-3)(x-10)^2 dx - \left(\frac{29}{5}\right)^2 = \frac{49}{25}$$

We use these results to find the distribution of  $\bar{G}$ .

$$E(\bar{G}) = E(G) = \frac{29}{5}$$

$$sd(\bar{G}) = \frac{sd(G)}{\sqrt{40}} = \frac{7}{5\sqrt{40}} = \frac{7}{10\sqrt{10}}$$

For  $Pr(\bar{G} < 6)$ , we can use `normcdf(-∞,6,E(̄G),sd(̄G))`, which gives  $Pr(\bar{G} < 6) = 0.82$

## 9.10 Normal Approximation of Sample Proportions

The distribution of the sample mean  $\bar{X}$  is normal with mean  $\bar{x} = \mu$  and the standard deviation  $s = \frac{\sigma}{\sqrt{n}}$ .

$$Pr(\bar{X} > a) = Pr\left(Z > \frac{a - \bar{x}}{s}\right) \quad Z \sim (0, 1)$$

### Example: FreeVCENotes Normal Approximation

Use the normal approximation to the binomial distribution to find the approximate probability, to 4 decimal places, that in the next 600 rolls of a fair die, the proportion of sixes rolled is less than 0.2.

Let  $\hat{P}$  be the proportion of sixes rolled

$$\mathbb{E}(\hat{P}) = p = \frac{1}{6}$$

$$\begin{aligned}\text{sd}(\hat{P}) &= \sqrt{\frac{p(1-p)}{n}} = \sqrt{\frac{\frac{1}{6} \left(\frac{5}{36}\right)}{600}} \\ &= \sqrt{\frac{1}{4320}}\end{aligned}$$

$$\hat{P} \sim N\left(\frac{1}{6}, \sqrt{\frac{1}{4320}}\right)$$

$$\begin{aligned}\Pr(\hat{P} < 0.2) &= \text{normcdf}\left(0, 0.2, \frac{1}{6}, \sqrt{\frac{1}{4320}}\right) \\ &= 0.9858\end{aligned}$$

## 9.11 Sample Proportions $\hat{P}$ without Normal Approximation (Methods)

**Mean, Variance, Standard Deviation** Using the mean and variance from the binomial, we can derive the following about the sample proportion  $\hat{P}$ :

$$\begin{aligned}\hat{P} &= \frac{X}{n}, \quad X \sim Bi(n, p) \\ \mathbb{E}(\hat{P}) &= p \quad \text{Var}(\hat{P}) = \frac{p(1-p)}{n} \quad \text{sd}(\hat{P}) = \sqrt{\text{Var}(\hat{P})}\end{aligned}$$

### Exam-style Question: 2016 VCAA Methods A17

Inside a container there are one million coloured building blocks. It is known that 20% of the blocks are red. A sample of 16 blocks is taken from the container. For samples of 16 blocks,  $\hat{P}$  is the random variable of the distribution of sample proportions of red blocks. (**Do not use a normal approximation.**)

Let  $X \sim Bi(16, 0.2)$  be a binomial variable representing the number of red blocks in the sample.

$$\hat{P} = \frac{X}{16} \implies X = 16\hat{P}$$

$$\begin{aligned}\Pr\left(\hat{P} \geq \frac{3}{16}\right) &= \Pr\left(X \geq \frac{3}{16} \times 16\right) \\ &= 0.6482 \quad \text{binomcdf}(16, 0.2, 3, 16)\end{aligned}$$

**Exam-style Question: 2016 VCAA Methods E2 B3d**

A supplier of laptops decides to take a sample of 100 new laptops from a number of different schools. For samples of size 100 from the population with a mean battery life of 3 hours 10 minutes and a standard deviation of 6 minutes,  $\hat{P}$  is the random variable of the distribution of sample proportions of laptops with battery life less than three hours. It is known that the probability that a single laptop's battery life is less than 3 hours is 0.0478. Find  $\Pr(\hat{P} \geq 0.06 | \hat{P} \geq 0.05)$  without a normal approximation.

Let  $Y$  be the number of laptops with battery less than 3 hours

$$Y \sim Bi(100, 0.0478)$$

$$\begin{aligned}\hat{P} &= \frac{Y}{100} \implies \Pr(\hat{P} \geq 0.06 | \hat{P} \geq 0.05) = \Pr(Y \geq 0.06 \times 100 | Y \geq 0.05 \times 100) \\ &= \Pr(Y \geq 6 | Y \geq 5) \\ &= \frac{\Pr(Y \geq 6)}{\Pr(Y \geq 5)} = 0.658\end{aligned}$$

## 9.12 Distribution of the sample mean

### 9.12.1 Central Limit Theorem

Let  $X$  be any random variable with mean  $\mu$  and standard deviation  $\sigma$ . Then, provided that the sample size  $n$  is large enough, the distribution of  $\bar{X}$  is approximately normal with mean  $E(\bar{X}) = \mu$  and  $sd(\bar{X}) = \frac{\sigma}{\sqrt{n}}$ .

### 9.12.2 Normal Approximation to the Binomial Distribution

If  $X$  is a binomial random variable with parameters  $n, p$ , then the distribution of  $X$  is approximately normal with mean  $\mu = np$  and standard deviation  $\sigma = \sqrt{np(1-p)}$  provided  $np > 5$  and  $n(1-p) > 5$ .

## 9.13 Confidence Intervals for the Population Mean

**Interpretation of a Confidence Interval** For a 95% confidence interval, we expect 95% of such intervals to contain the population mean  $\mu$ . Whether or not a particular confidence interval contains  $\mu$  is generally unknown.

**Point Estimates** The value of the sample mean  $\bar{x}$  can be used to estimate the population mean  $\mu$ , as this is a single-valued estimate, it is called a point estimate of  $\mu$ .

**Interval Estimates** An interval estimate for the population mean  $\mu$  is called a confidence interval for  $\mu$ .

**C% Confidence Interval** An approximate C% confidence interval for  $\mu$  is given by

$$\left( \bar{x} - z \frac{\sigma}{\sqrt{n}}, \bar{x} + z \frac{\sigma}{\sqrt{n}} \right)$$

where  $z \ni \Pr(-z < Z < z) = C\%$ ,  $\bar{x}$  is the sample mean,  $\sigma$  is the standard deviation of the population and  $n$  is the size of the sample from which  $\bar{x}$  was calculated.

The values of  $z$  for common confidence intervals:

- 90%  $\rightarrow z = 1.6449$
- 95%  $\rightarrow z = 1.9600$
- 99%  $\rightarrow z = 2.5758$

To find the  $z$  score to use for any C% confidence interval in CAS:  $\text{invnorm}(\frac{C}{2}, 0, 1)$  will give you the value for  $z$ .

**Exam-style Question: VCAA Spesh 2017 Exam 2 A19**

A confidence interval is to be used to estimate the population mean  $\mu$  based on a sample mean  $\bar{x}$ . To decrease the width of a confidence interval by 75%, the sample size must be multiplied by a factor of...

To reduce by 75% is the equivalent to making it a quarter the width, i.e. dividing by four:

$$\frac{\sigma}{4\sqrt{n}} = \frac{\sigma}{\sqrt{16n}}$$

Therefore the sample size must be multiplied by a factor of 16.

### Exam-style Question: 2023 MAV Methods E2 A16

A survey found that 110 out of 400 Year 12 students study more than 2 hours per night. An approximate 95% confidence interval for the proportion of Year 12 students who study more than 2 hours per night is (0.2312, 0.3188). If the width of this confidence interval was to be decreased by 70%, the sample size must be:

$$\begin{aligned}W_1 &= 2z \frac{\sigma}{\sqrt{n_1}}, W_2 = 2z \frac{\sigma}{\sqrt{n_2}} \\W_2 &= 2z \frac{\sigma}{\sqrt{n_2}} = 0.3 \times 2z \frac{\sigma}{\sqrt{n_1}} \\ \frac{1}{\sqrt{n_2}} &= 0.3 \frac{1}{\sqrt{n_1}} \\ \Rightarrow n_2 &= \frac{100}{9} n_1\end{aligned}$$

$$\text{solve} \left( \frac{1}{\sqrt{m}} = 0.3 \cdot \frac{1}{\sqrt{n}}, m \right) \quad m = \frac{100 \cdot n}{9}$$

Where  $m$  is the new sample size and  $n$  is the original sample size.

The sample size must be increased by a factor of  $\frac{100}{9}$

## 9.14 Hypothesis Testing for Mean

**Null hypothesis** The null hypothesis is denoted by  $H_0$  says that the sample is drawn from a population which has the same mean as before (the mean has not changed after taking the sample). Under this hypothesis, any difference between a sample statistic and a population parameter is explained by sample-sample variation.

**Alternative hypothesis** The alternative hypothesis  $H_1$  says that the population mean has changed.

**p-Values** The  $p$  value is the probability of observing a value of the sample statistic as extreme as or more extreme than the one observed, assuming that the null hypothesis is true.

**Statistical Significance** The significance level represents the threshold of unlikelihood that a result must have to cast sufficient doubt on the null hypothesis. This is denoted by  $\alpha$ .

If the  $p$ -value is less than  $\alpha$ , we reject the null hypothesis in favour of the alternative hypothesis. If the  $p$ -value is greater than  $\alpha$ , we do not reject the null hypothesis.

**z-test** is the name for the hypothesis test for a mean of a sample drawn from a normally distributed population with known standard deviation.

### 9.14.1 One-tail tests

For directional alternative hypotheses, one-tail tests are used to calculate  $p$ -values.

For  $H_1 : \mu > x$  the  $p$ -value is calculated considering only values in the upper tail of the normal curve.

For  $H_1 : \mu < x$  the  $p$ -value is calculated considering only values in the lower tail of the normal curve.

### 9.14.2 Two-tail tests

Non-directional alternative hypothesis  $p$ -values are determined with two-tail tests.  $H_1 : \mu \neq x$ .

$$p = \Pr(|\bar{X} - \mu| \geq |\bar{x} - \mu|)$$

$p$ -value (two-tail) =  $2 \times p$ -value (one-tail)

### Example: Cambridge Modulus Bullshit

Suppose that the weight  $X$ kg of sand in a bag is a normally distributed random variable with a mean of 50kg and a standard deviation of 1.5kg. A random sample of 10 bags is taken.

- a) Find the probability that the mean weight of the 10 bags in the sample differs by 1kg or more from the population mean.

$$\begin{aligned}\Pr(|\bar{X} - \mu| \geq 1) &= \Pr\left(\left|\frac{\bar{X} - \mu}{\sigma/\sqrt{n}}\right| \geq \frac{1}{\frac{1.5}{\sqrt{10}}}\right) \\ &= \Pr(|Z| \geq 2.108) \\ &= 2 \times \Pr(Z \leq -2.108) \\ &= 0.035\end{aligned}$$

- b) Suppose that the mean weight of the 10 bags is 49.1kg

- i) Determine the  $p$  value appropriate to the following hypotheses:

$$H_0 : \mu = 50 \quad H_1 : \mu \neq 50$$

$$\begin{aligned}p &= \Pr(|\bar{X} - \mu| \geq |\bar{x} - \mu|) \\ &= \Pr\left(|Z| \geq \left|\frac{49.1 - 50}{1.5/\sqrt{10}}\right|\right) \\ &= \Pr(|Z| \geq |-1.897|) \\ &= 2 \Pr(Z \geq 1.897) = 0.0578\end{aligned}$$

- ii) What is your conclusion at  $\alpha = 0.05$ ?

Since  $p$  is greater than  $\alpha$ , there is insufficient evidence to conclude that the mean weight of the bags is not 50kg.

#### 9.14.3 Relation to Confidence Intervals

Consider the fact of the real number line:

$$a \in (b - c, b + c) \iff |a - b| < c \iff b \in (a - c, a + c)$$

Suppose we have:

$$H_0 : \mu = \mu_0 \quad H_1 : \mu \neq \mu_0$$

Then:

$$\mu_0 \notin \left(\bar{x} - 1.96 \frac{\sigma}{\sqrt{n}}, \bar{x} + 1.96 \frac{\sigma}{\sqrt{n}}\right) \iff \bar{x} \notin \left(\mu_0 - 1.96 \frac{\sigma}{\sqrt{n}}, \mu_0 + 1.96 \frac{\sigma}{\sqrt{n}}\right)$$

Hence the 95% confidence interval does not contain  $\mu_0$  if and only if we should reject  $H_0$  at a 5% significance.

#### 9.14.4 Hypothesis Testing Errors

**Type I** Rejecting the null hypothesis when it is true.  $\Pr(\text{Type I}) = \Pr(H_0 \text{ rejected} | H_0 \text{ true}) = \text{level of significance of test}$

**Type II** Not rejecting the null hypothesis when it is false.  $\Pr(\text{Type II}) = \Pr(H_0 \text{ not rejected} | H_0 \text{ false})$

**Exam-style Question: VCAA 2023 Specialist E2 Sample Q7**

**Question 7**

The time taken by a machine to make electronic components varies normally with a mean of 20 seconds and a standard deviation of 2 seconds. After the machine is serviced, it is believed that the mean time taken has been reduced to 18.5 seconds with the standard deviation remaining the same.

A statistical test is proposed to check whether there is any evidence of a 1.5 second reduction in the mean time taken to make components. The test statistic will be the mean time taken to make a random sample of 16 such components. The type I error for the test will be  $\alpha = 5\%$  with a critical sample mean of 19.2 seconds.

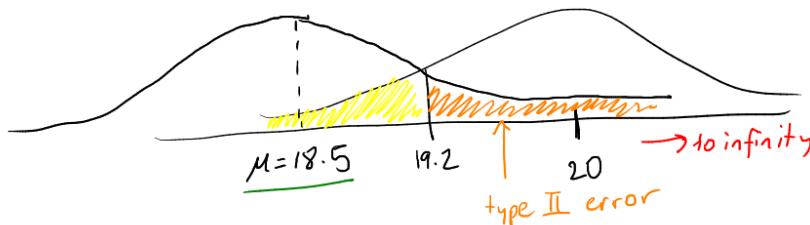
The type II error ( $\beta$ ) for the test is closest to

- A. 8%
- B. 34%
- C. 36%
- D. 46%
- E. 95%

Type II = not rejecting when false

$$\text{std}(\bar{X}) = \frac{2}{\sqrt{n}} = \frac{2}{\sqrt{16}} \quad \text{normCdf}\left(19.2, \infty, 18.5, \frac{2}{\sqrt{16}}\right)$$

0.080756711166



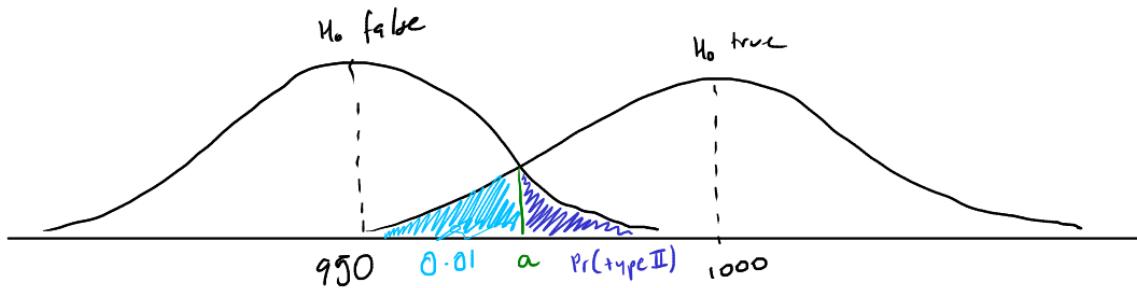
**Exam-style Question: Heffernan 2023 Spesh E2 A20**

A battery company claims that their Type A battery has an average lifetime of 1000 hours and a standard deviation of 100 hours. Unconvinced of the company's claim, a consumer rights organisation conducts a one-tailed statistical test at the 1% level of significance and obtains a random sample of 50 Type A batteries.

If the actual average lifetime of a Type A battery is 950 hours, the probability of making a type II error is...

Recall that  $\Pr(\text{typeII}) = \Pr(\text{Accept } H_0 | H_0 \text{ false})$ .

First, we need to find the critical sample mean, that is the value of  $a$  such that  $\Pr(\bar{X} < a | \mu = 1000) = 0.01$  (rejecting the null hypothesis). Using CAS we find  $a = 967.1005$ , then we use this info to find the type II error.



$$\text{solve}\left(\text{invNorm}(0.01) = \frac{\alpha - 1000}{10 \cdot \sqrt{2}}, \alpha\right)$$

$\alpha = 967.100472814$

$$\text{normCdf}(967.1005, \infty, 950, 10 \cdot \sqrt{2}) \\ 0.113295385231$$

$$\Pr(\text{Type II}) = \Pr(\bar{X} > 967.1005 \mid \mu = 950) \\ = 0.1133$$

#### Exam-style Question: VCAA 2021 Specialist E2 QB6

The maximum load of a lift in a chocolate company's office building is 1000kg. The masses of employees who use the lift are normally distributed with a mean of 75kg and a standard deviation of 8kg. On a particular morning there are  $n$  employees who use the lift.

- a) What is the maximum possible value of  $n$  for there to be a less than 1% chance of the lift exceeding the maximum load? (2 marks)

$W \sim N(75, 8)$  Let  $W_i$  be a random variable identically distributed to  $W$ ,  $T = \sum_{i=1}^n W_i$

$$\mathbb{E}(T) = 75n \quad \text{sd}(T) = 8\sqrt{n} \implies T \sim N(75n, 8\sqrt{n})$$

$$\Pr(T < 1000) = \Pr\left(Z < \frac{1000 - 75n}{8\sqrt{n}}\right) > 0.99$$

$$\frac{1000 - 75n}{8\sqrt{n}} > 2.3263$$

$$\implies n = 12 \text{ (nearest integer)}$$

Clare, who is one of the employees, likes to have a hot drink after she exits the lift. The time taken for a drink to be dispensed from the hot drink machine is normally distributed with a mean of 2 minutes and a standard deviation of 0.5 minutes. Time taken to dispense successive drinks are independent.

- b) Clare has a meeting at 9:00am and at 8:52 am she is fourth in the queue for a hot drink. Assume that the waiting time between hot drinks dispensed is negligible and that it takes Clare 0.5 minutes to get from the drink machine to the meeting room. What is the probability, correct to four decimal places, that Clare will get to her meeting on time? (2 marks)

$$T \sim N\left(2, \frac{1}{2}\right)$$

$$\Pr\left(4T + \frac{1}{2} < 8\right) = \Pr(4T < 15/2)$$

$$X = 4T \sim N(8, 1)$$

$$\Pr\left(X > \frac{15}{2}\right) = 0.3085$$

Clare is a statistician for the company. The number of chocolate bars sold daily is normally distributed with a mean of 60000 and a standard deviation of 5000. To increase sales, the company decides to run an advertising campaign. After the campaign, the mean daily sales from 14 randomly selected days is 63500. Clare has been asked to investigate whether the campaign was effective, and so she performs a one-tailed test at the 1% level of significance.

c)i) Write down a null and alternative hypothesis. (1 mark)

$$H_0 : \mu = 60000 \quad H_1 : \mu > 60000$$

ii) Determine the  $p$  value, correct to 4 decimal places, for this test. (1 mark)

$$S \sim N(60000, 5000) \quad p = \Pr(\bar{S} > 63500 | \mu = 60000) = \Pr\left(Z > \frac{63500 - 60000}{\frac{5000}{\sqrt{14}}}\right) = 0.0044$$

**Note:** Menu+6+7+1 can also conduct a  $z$  test for this hypothesis.

iii) Giving a reason, state whether there is any evidence for the success of the campaign? (1 mark)

$p=0.0044<0.01$ , and therefore there is sufficient evidence to reject  $H_0$  and conclude the campaign was effective.

d) Find the range of values for the mean daily sales of another randomly selected 14 days that would lead to rejecting the null hypothesis at 1% level of significance.

$$\Pr\left(Z > \frac{\bar{x} - 60000}{\frac{5000}{\sqrt{14}}}\right) \leq 0.01$$

$$2.3263 \leq \frac{\bar{x} - 60000}{\frac{5000}{\sqrt{14}}}$$

$$\implies \bar{x} \geq 63109$$

e) The advertising campaign has been successful to the extent that the mean daily sales is now 63000. Another test is conducted at 5% significance level. Find the probability of the null hypothesis being incorrectly accepted, to 3 decimal places.

$$\Pr\left(Z > \frac{s - 60000}{\frac{5000}{\sqrt{14}}}\right) = 0.05 \implies s = 62198.03$$

$$\Pr(\bar{s} < 62198.03 | \mu = 63000) = 0.274$$

**Question 6** (8 marks)

The heights of mature water buffaloes in northern Australia are known to be normally distributed with a standard deviation of 15 cm. It is claimed that the mean height of the water buffaloes is 150 cm.

To decide whether the claim about the mean height is true, rangers selected a random sample of 50 mature water buffaloes. The mean height of this sample was found to be 145 cm.

A one-tailed statistical test is to be carried out to see if the sample mean height of 145 cm differs significantly from the claimed population mean of 150 cm.

Let  $\bar{X}$  denote the mean height of a random sample of 50 mature water buffaloes.

- a. State suitable hypotheses  $H_0$  and  $H_1$  for the statistical test. 0 mark

$$H_0: \mu = 150$$

$$H_1: \mu < 150 \quad \text{*one-tail}$$

- b. Find the standard deviation of  $\bar{X}$ . 1 mark

$$sd(\bar{X}) = \frac{15}{\sqrt{50}} = \frac{3\sqrt{2}}{2}$$

- c. Write down an expression for the  $p$  value of the statistical test and evaluate your answer correct to four decimal places. 2 marks

$$p = \Pr(\bar{X} < 145 | \mu = 150)$$

$$p = 0.0092 \quad \text{*menu + 6+6+1 see 9.1.17}$$

- d. State with a reason whether  $H_0$  should be rejected at the 5% level of significance. 1 mark

$H_0$  should be rejected as  $p=0.0092$  is less than the 0.05

threshold of significance.

- e. What is the smallest value of the sample mean height that could be observed for  $H_0$  to be not rejected? Give your answer in centimetres, correct to two decimal places. 1 mark

$$\Pr(\bar{X} < \bar{h} | \mu = 150) = 0.05 \quad Z \sim N(0,1)$$

$$\Pr(Z < \frac{\bar{h} - 150}{\frac{3\sqrt{2}}{2}}) = 0.05 \Rightarrow \bar{h} = 146.51 \text{ cm}$$

- f. If the true mean height of all mature water buffaloes in northern Australia is in fact 145 cm, what is the probability that  $H_0$  will be accepted at the 5% level of significance? Give your answer correct to two decimal places.

(1 mark)

$$\Pr(\bar{X} > 146.51 \mid \mu = 145) \quad Z \sim N(0,1)$$

$$= \Pr\left(Z > \frac{146.51 - 145}{\frac{3\sqrt{2}}{\sqrt{2}}}\right) = 0.24$$


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- g. Using the observed sample mean of 145 cm, find a **99% confidence interval** for the mean height of all mature water buffaloes in northern Australia. Express the values in your confidence interval in centimetres, correct to one decimal place.

(1 mark)

$$CI = (139.5, 150.5)$$


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**Question 6** (9 marks)

A company produces packets of noodles. It is known from past experience that the mass of a packet of noodles produced by one of the company's machines is normally distributed with a mean of 375 grams and a standard deviation of 15 grams.

To check the operation of the machine after some repairs, the company's quality control employees select two independent random samples of 50 packets and calculate the mean mass of the 50 packets for each random sample.

- a. Assume that the machine is working properly. Find the probability that at least one random sample will have a mean mass between 370 grams and 375 grams. Give your answer correct to three decimal places.

(2 marks)

$$M \sim N(375, 15)$$

$$E(\bar{M}) = 375 \quad sd(\bar{M}) = \frac{15}{\sqrt{50}} = \frac{3\sqrt{2}}{2}$$

$$\therefore \bar{M} \sim N(375, \frac{3\sqrt{2}}{2})$$

$$Pr(370 < \bar{M} < 375) = 0.491$$

$$X \sim Bi(2, 0.491) \quad Pr(X \geq 1) = 0.741$$

- b. Assume that the machine is working properly. Find the probability that the means of the two random samples differ by less than 2 grams. Give your answer correct to three decimal places.

(3 marks)

$$\bar{M}_1 \sim N(375, \frac{3\sqrt{2}}{2}) \quad \bar{M}_2 \sim N(375, \frac{3\sqrt{2}}{2})$$

$$E(\bar{M}_1 - \bar{M}_2) = 0 \quad sd(\bar{M}_1 - \bar{M}_2) = 3$$

$$Pr(-2 < \bar{M}_1 - \bar{M}_2 < 2) = 0.495$$

To test whether the machine is working properly after the repairs and is still producing packets with a mean mass of 375 grams, the two random samples are combined and the mean mass of the 100 packets is found to be 372 grams. Assume that the standard deviation of the mass of the packets produced is still 15 grams. A two-tailed test at the 5% level of significance is to be carried out.

- c. Write down suitable hypotheses  $H_0$  and  $H_1$  for this test.

(1 mark)

$$H_0: M = 375$$

$$H_1: M \neq 375$$

- d. Find the  $p$  value for the test, correct to three decimal places.

(1 mark)

$$p = 0.046$$

- e. Does the mean mass of the sample of 100 packets suggest that the machine is working properly at the 5% level of significance for a two-tailed test? Justify your answer.

(1 mark)

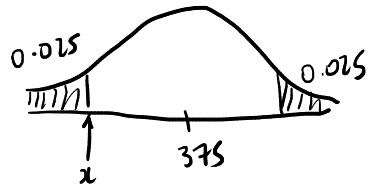
$$H_0, \rho (=0.046) < 0.05$$

$\therefore$  reject  $H_0 \Rightarrow$  the machine is not working properly

- f. What is the smallest value of the mean mass of the sample of 100 packets for  $H_0$  to be **not** rejected? Give your answer correct to one decimal place.

(1 mark)

$$x = 372.1g \quad \text{#invnorm}(0.025, 375, \frac{15}{\sqrt{100}})$$



**Question 6** (10 marks)

A real estate agent's income is comprised of a fixed monthly payment of \$5000 plus a commission of \$4000 for each house sold. The agent may sell up to three houses in a month with the following probability distribution, where  $H$  is the number of houses sold.

$h$	0	1	2	3
$\Pr(H = h)$	0.2	0.6	0.19	0.01

- a. Find the agent's expected total income each month. Give your answer in dollars, correct to the nearest dollar. 2 marks

$$\underline{I} = 5000 + 4000H$$

$$E(H) = 0 + 0.6 + 0.38 + 0.03 = 1.01 \checkmark$$

$$E(I) = 5000 + 4000(1.01) = \$9040 \checkmark$$

- b. What extra amount of commission should the agent request for each house sold so that their expected monthly income increases by \$2000? Give your answer in dollars and cents, correct to the nearest cent. 2 marks

$$2000 = a \times 0.6 + 2a \times 0.19 + 3a \times 0.01 \checkmark$$

$$a = \$1980.20 \checkmark$$

To prepare a certain house for sale, the agent recommends that the garden be landscaped and replanted. The time taken for a contractor to landscape the garden is normally distributed with a mean of 18 hours and a standard deviation of four hours. The time taken for replanting is independent of the time taken for landscaping and is normally distributed with a mean of 24 hours and a standard deviation of six hours.

- c. What is the probability, correct to four decimal places, that the garden can be landscaped and replanted within a week? Assume that the contractor will work eight hours per day for five days of the week. 2 marks

$$L \sim N(18, 4) \quad R \sim N(24, 6)$$

$$T = L + R$$

$$E(T) = 42 \quad \text{sd}(T) = 2\sqrt{13}$$

$$\therefore T \sim N(42, 2\sqrt{13}) \checkmark$$

$$\Pr(T < 40) = 0.3908 \checkmark$$

- d. What period of time should the agent allow the contractor to complete the tasks of landscaping and replanting, in order to be 90% confident that these tasks will be completed within this period of time? Give your answer in hours, correct to two decimal places. 1 mark

$$\Pr(T < a) = 0.90$$

$$\Pr\left(Z < \frac{a - 42}{2\sqrt{3}}\right) = 0.90$$

$$a = 51.24 \text{ hours } \checkmark$$

- e. Before the annual income review, the agent believes that the company's remuneration level is below the industry average of \$115 000 per annum, with an industry standard deviation of \$12 000. To test this hypothesis, the agent takes a random sample of 36 of the company's employees and finds their mean income to be \$110 800 per annum.

Assuming an industry standard deviation of \$12 000, carry out a one-tailed statistical test at the 5% level of significance to ascertain whether the sample mean of \$110 800 per annum supports the agent's belief. 3 marks

$$H_0: \mu = 115\ 000 \quad H_1: \mu < 115\ 000 \quad \alpha = 0.05 \checkmark$$

$$p = \Pr(\bar{X} \leq 110\ 800 \mid \mu = 115\ 000)$$

$$= \Pr\left(Z \leq \frac{110\ 800 - 115\ 000}{12\ 000}\right)$$

$$= 0.0179 \checkmark$$

$$p = 0.0179 < 0.05$$

$\therefore$  sufficient evidence to reject  $H_0$ , agent's claim supported  $\checkmark$

**Question 5** (10 marks)

A machine is calibrated to produce ball bearings such that their diameters are normally distributed with a mean of 0.5 cm and a standard deviation of 0.005 cm. To determine whether the machine is working correctly, random samples of 10 ball bearings are selected at various times and the mean diameter of the 10 ball bearings in each sample is calculated.

For a particular sample of 10 ball bearings, the mean diameter is 0.5003 cm. It is proposed to carry out a statistical test at the 5% level of significance to determine whether the machine is now producing ball bearings with a mean diameter greater than 0.5 cm and possibly needs resetting. Assume that the standard deviation is still 0.005 cm.

- a. Write down the mean and the standard deviation of the sampling distribution for samples of 10 ball bearings. Give the value of the standard deviation correct to four decimal places.

(2 marks)

Let  $\bar{D}$  be the sampling distribution of diameters of 10 balls

$$E(\bar{D}) = 0.5 \checkmark \quad sd(\bar{D}) = \frac{0.005}{\sqrt{10}} = 0.0016 \checkmark$$

- b. Write down suitable null and alternative hypotheses for the statistical test.

(1 mark)

$$H_0: \mu = 0.5 \quad H_1: \mu > 0.5 \checkmark$$

- c. Find, correct to three decimal places, the  $p$  value for the statistical test.

(1 mark)

$$p = 0.425 \checkmark$$

- d. Draw an appropriate conclusion about the hypotheses in **part b.** from the  $p$  value found in **part c.** Give a reason involving  $p$  for your conclusion.

(1 mark)

$$p = 0.425 > 0.05$$

$\therefore$  insufficient evidence to reject  $H_0$   $\checkmark$

- e. Find the largest sample mean of 10 ball bearings that could be observed for the null hypothesis not to be rejected at the 5% level of significance. Assume that the machine is still producing ball bearings with a standard deviation of 0.005 cm. Give your answer correct to four decimal places.

(1 mark)

$$Pr(\bar{D} < \bar{d} | \mu = 0.5) > 0.05$$

$$\bar{d} = 0.5026 \text{ cm} \checkmark$$

The settings of the machine will be checked if a sample mean  $\bar{x}$  of 10 ball bearings falls outside the interval  $(a, b)$ , where  $\Pr(\bar{x} < a) = 0.01$  and  $\Pr(\bar{x} > b) = 0.01$

- f. Find the values of  $a$  and  $b$ , correct to three decimal places, assuming that the machine is producing ball bearings with a mean diameter of 0.5 cm and a standard deviation of 0.005 cm. 2 marks

$$a = 0.496 \quad \checkmark$$

$$b = 0.504 \quad \checkmark$$

- g. On a certain day, five random samples of 10 ball bearings are selected.

Find the probability that only one of the five sample means falls outside the interval found in part f. Give your answer correct to three decimal places. 2 marks

$$X \sim B(5, 0.02) \quad \checkmark$$

$$\Pr(X=1) = 0.092 \quad \checkmark$$

## 10 Differential Calculus

### 10.1 Derivatives of $x=f(y)$

For  $x = f(y)$  where  $f$  is a one-to-one function:

$$\frac{dy}{dx} = \frac{1}{\frac{dx}{dy}}, \frac{dx}{dy} \neq 0$$

### 10.2 Derivatives of Inverse Circular Functions

### 10.3 Second Derivatives

### 10.4 Points of Inflection

### 10.5 Related Rates

### 10.6 Rational Functions

## 11 Integral Calculus

### 11.1 Rules

#### 11.1.1 Definite Integral

The definite integral on interval  $[a, b]$  denotes the signed area enclosed by the graph  $y = f(x)$ , the  $x$ -axis, and the lines  $x = a$  and  $x = b$ .

$$\int_a^b f(x) dx = F(b) - F(a)$$

where  $F(x)$  is any antiderivative of  $f(x)$

### 11.2 Inverse Circular Functions

$$\begin{aligned}\int \frac{1}{\sqrt{a^2 - x^2}} dx &= \arcsin\left(\frac{x}{a}\right) + C, x \in (-a, a) \\ \int \frac{-1}{\sqrt{a^2 - x^2}} dx &= \arccos\left(\frac{x}{a}\right) + C, x \in (-a, a) \\ \int \frac{a}{a^2 + x^2} dx &= \arctan\left(\frac{x}{a}\right) + C, x \in \mathbb{R}\end{aligned}$$

### 11.3 u-Sub

$$\int f(u) \frac{du}{dx} dx = \int f(u) du$$

**Linear substitutions** Antiderivatives of expressions in the form  $f(x)[g(x)]^n$  for a linear function  $g$  can be found using linear substitution:

#### Exam-style Question:

Evaluate  $\int_0^1 xe^{-x^2} dx$ .

$$\begin{aligned}\int_0^1 xe^{-x^2} dx &= \frac{1}{2} \int_0^1 (2x)e^{-x^2} dx \\ u &= -x^2 \quad \frac{du}{dx} = -2x \quad x = 0 \implies u = 0, x = 1 \implies u = -1 \\ &= \frac{-1}{2} \int_0^{-1} e^u du \\ &= \frac{-1}{2} [e^u]_0^{-1} \\ &= \frac{-1}{2} (e^{-1} - 1) \\ &= \frac{1}{2} - \frac{1}{2e}\end{aligned}$$

**Exam-style Question: 2006 NEAP E2 A11**

Using a suitable substitution,  $\int_0^{\frac{\pi}{4}} \left( \frac{\cos x}{\sin x + \cos^2 x} \right) dx$  can be expressed as:

Let  $u = \sin x$

$$\int \frac{\cos x}{\sin x + (1 - \sin^2 x)} dx = \int \frac{1}{u + 1 - u^2} du$$

**Exam-style Question:**

Using the substitution  $u = \pi - x$ ,

a) Show that  $\int_0^{\pi} \frac{x \sin x}{1 + \cos^2 x} dx = \int_0^{\pi} \frac{(\pi - x) \sin x}{1 + \cos^2 x} dx$ .

$$\begin{aligned} u &= \pi - x & x &= \pi - u & \frac{du}{dx} &= -1 & du &= -dx \\ \int_0^{\pi} \frac{x \sin x}{1 + \cos^2 x} dx &= \int_{\pi}^0 \frac{(\pi - u) \sin(\pi - u)}{1 + \cos^2(\pi - u)} (-du) \\ &= \int_0^{\pi} \frac{(\pi - u) \sin(\pi - u)}{1 + \cos^2(\pi - u)} du \\ &= \int_0^{\pi} \frac{(\pi - x) \sin(x)}{1 + \cos^2 x} dx \quad (\text{Because } u \text{ is just a dummy variable}) \end{aligned}$$

b) Hence deduce that  $\int_0^{\pi} \frac{x \sin x}{1 + \cos^2 x} dx = \frac{\pi^2}{4}$ .

$$\begin{aligned} \int_0^{\pi} \frac{x \sin x}{1 + \cos^2 x} dx &= \int_0^{\pi} \frac{\pi \sin x}{1 + \cos^2 x} dx - \int_0^{\pi} \frac{x \sin x}{1 + \cos^2 x} dx \\ 2 \int_0^{\pi} \frac{x \sin x}{1 + \cos^2 x} dx &= \pi \int_0^{\pi} \frac{\sin x}{1 + \cos^2 x} dx \implies \int_0^{\pi} \frac{x \sin x}{1 + \cos^2 x} dx = \frac{\pi}{2} \int_0^{\pi} \frac{\sin x}{1 + \cos^2 x} dx \\ v &= \cos x, dx = \frac{-1}{\sin x} du, x = 0 \rightarrow v = 1, x = \pi \rightarrow v = -1 \\ \pi \int_0^{\pi} \frac{\sin x}{1 + \cos^2 x} dx &= -\pi \int_1^{-1} \frac{1}{1 + u^2} du \\ &= \pi \int_{-1}^1 \frac{1}{1 + u^2} du = \pi [\arctan u]_{-1}^1 \\ &= \frac{\pi^2}{2} \\ \therefore \int_0^{\pi} \frac{x \sin x}{1 + \cos^2 x} dx &= \frac{1}{2} \cdot \frac{\pi^2}{2} = \frac{\pi^2}{4} \end{aligned}$$

## 11.4 Integration by Trig Identities

Integrals of form  $\int \sin^m(x) \cos^n(x) dx$  can be considered in three cases:

**Case 1: Power of sine is odd** If  $m$  is odd, let  $m = 2k + 1, k \in \mathbb{Z}$

$$\sin^{2k+1}(x) = (\sin^2 x)^k \sin x = (1 - \cos^2 x)^k \sin x$$

We can then use the substitution  $u = \cos x$  to evaluate integrals.

**Case 2: Power of cosine is odd** If  $m$  is even and  $n$  is odd, let  $n = 2k + 1, k \in \mathbb{Z}$

$$\cos^{2k+1}(x) = (\cos^2 x)^k \cos x = (1 - \sin^2 x)^k \cos x$$

We can then use the substitution  $u = \sin x$  to evaluate integrals.

**Case 3: Both powers are even** If both  $m$  and  $n$  are even, we use the identities:

$$\sin^2 x = \frac{1}{2} (1 - \cos(2x)) \quad \cos^2 x = \frac{1}{2} (1 + \cos(2x)) \quad \sin(2x) = 2 \sin(x) \cos(x)$$

**Products to Sums Identities** Recall the product to sum identities:

$$2 \cos x \cos y = \cos(x - y) + \cos(x + y) \quad 2 \sin x \sin y = \cos(x - y) - \cos(x + y) \quad 2 \sin x \cos y = \sin(x + y) + \sin(x - y)$$

We can also use these for integration in appropriate questions.

## 11.5 Partial Fractions

**Proper Fractions** If  $g(x)$  and  $h(x)$  are polynomials then  $f(x) = \frac{g(x)}{h(x)}$  is a rational function. If the degree of  $g$  is less than the degree of  $h$  then  $f(x)$  is a proper fraction.

For **proper fractions**, we resolve into proper fractions with the following rules:

- For every linear factor  $ax + b$  in the denominator, there will be a partial fraction of form  $\frac{A}{ax+b}$
- For every repeated linear factor  $(ax + b)^2$  in the denominator, there will be two partial fractions of form  $\frac{A}{ax+b}$  and  $\frac{B}{(ax+b)^2}$
- For every irreducible quadratic factor  $ax^2 + bx + c$  in the denominator, there will be a partial fraction of the form  $\frac{Ax+B}{ax^2+bx+c}$ .
- For every repeated irreducible quadratic factor  $(ax^2 + bx + c)^2$  in the denominator, there will be two partial fractions of form  $\frac{Ax+B}{ax^2+bx+c}$  and  $\frac{Cx+D}{(ax^2+bx+c)^2}$

For **improper fractions**, those where the degree of the numerator is greater than the denominator, we use polynomial division to first create a proper fraction then resolve as normal.

## 11.6 Integration by Parts

$$\begin{aligned} \int u \frac{dv}{dx} dx &= uv - \int v \frac{du}{dx} dx \\ \int_a^b u \frac{dv}{dx} dx &= [uv]_a^b - \int_a^b v \frac{du}{dx} dx \end{aligned}$$

**Exam-style Question: VCAA 2007 Spesh E2 B2**

Let  $f(x) = x \arctan(x)$ .

a) Find  $f'(x)$  and calculate the slope of  $f$  at  $x = 0$ .

$$\begin{aligned} f'(x) &= \arctan(x) + x \cdot \frac{1}{x^2 + 1} = \arctan(x) + \frac{x}{x^2 + 1} \\ f'(0) &= 0 \end{aligned}$$

d) Use the result for  $f'(x)$  in part a to show that an antiderivative of  $\arctan(x)$  is

$$x \arctan(x) - \frac{1}{2} \ln(1 + x^2)$$

$$\begin{aligned} f'(x) &= \arctan(x) + \frac{x}{x^2 + 1} \\ \int f'(x) dx &= \int \frac{x}{x^2 + 1} dx + \int \arctan(x) dx \\ \text{Let } u = 1 + x^2 &\quad f(x) = \int \arctan(x) dx + \frac{1}{2} \int \frac{1}{u} du \\ \int \arctan(x) dx &= x \arctan(x) - \frac{1}{2} \ln(u) + c \\ &= x \arctan(x) - \frac{1}{2} \ln(1 + x^2) \text{ is an antiderivative as required} \end{aligned}$$

## 11.7 Properties of the Definite Integral

$$\int_a^b f(x) dx = \int_a^c f(x) dx + \int_c^b f(x) dx, a < c < b$$

$$\int_a^a f(x) dx = 0$$

$$\int_a^b kf(x) dx = k \int_a^b f(x) dx$$

$$\int_a^b f(x) \pm g(x) dx = \int_a^b f(x) dx \pm \int_a^b g(x) dx$$

$$\int_a^b f(x) dx = - \int_b^a f(x) dx$$

## 11.8 Area Between Curves

Let  $f$  and  $g$  be continuous functions on the interval  $[a, b]$  such that  $\forall x \in [a, b] f(x) \geq g(x)$ . The area of the region bounded between the two curves and the lines  $x = a$  and  $x = b$  can be found by evaluating:

$$\int_a^b f(x) dx - \int_a^b g(x) dx = \int_a^b f(x) - g(x) dx$$

When the graphs intersect on the interval, you must evaluate an integral for each section.

## 11.9 Volumes of Solids of Revolution

By rotating a function around an axis you form a solid of revolution.

**Revolution around the x-axis** If the region being rotated is bounded by  $y = f(x)$ ,  $x = a$ ,  $x = b$  and the  $x$ -axis, then:

$$V = \pi \int_a^b f(x)^2 dx$$

**Revolution around the y-axis** If the region being rotated is bounded by  $x = f(y)$ ,  $y = a$ ,  $y = b$  and the  $y$ -axis, then:

$$V = \pi \int_a^b f(y)^2 dy$$

**Regions not bound by an axis** If the region to be rotated is bounded by two functions instead of by an axis, use the area between two curves formula:

$$V = \pi \int_a^b (f(x))^2 - (g(x))^2 dx$$

### 11.10 Lengths of Curves in Plane

The length of a curve of  $f(x)$  (for  $f$  is differentiable and  $f'$  is continuous) from  $x = a$  to  $x = b$  is given by:

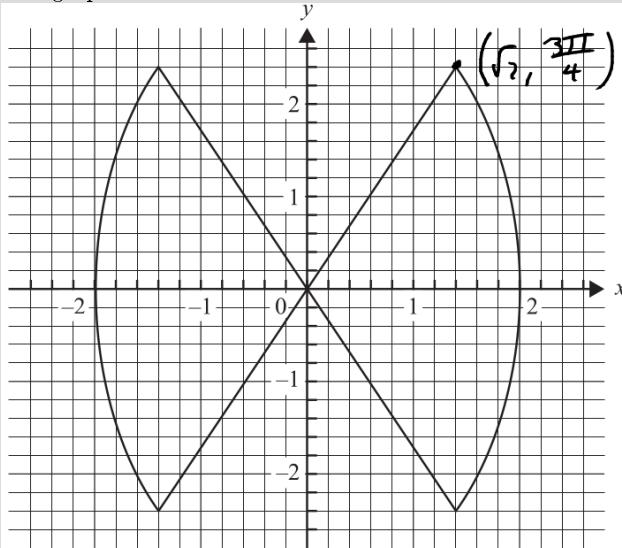
$$L = \int_a^b \sqrt{1 + \left(\frac{dy}{dx}\right)^2} dx = \int_a^b \sqrt{1 + (f'(x))^2} dx$$

#### Exam-style Question: VCAA Spesh 2017 E2 B3e

A brooch is designed using inverse circular functions. The edges of the brooch in the first and third quadrants are described by these piecewise functions:

$$\text{Q1: } f(x) = \begin{cases} 3 \arcsin\left(\frac{x}{2}\right) & 0 \leq x \leq \sqrt{2} \\ 3 \arccos\left(\frac{x}{2}\right) & \sqrt{2} < x \leq 2 \end{cases} \quad \text{Q3: } g(x) = \begin{cases} -3 \arccos\left(\frac{-x}{2}\right) & -2 \leq x < -\sqrt{2} \\ -3 \arcsin\left(\frac{-x}{2}\right) & -\sqrt{2} \leq x \leq 0 \end{cases}$$

The graph of the whole brooch is shown below:



The perimeter of the brooch has a gold border. Show that the length of the gold border needed is given by a definite integral of the form  $\int_0^2 \sqrt{a + \frac{b}{4-x^2}} dx$ , where  $a, b \in \mathbb{R}$ . Find the values of  $a$  and  $b$ .

$$f'(x) = \begin{cases} \frac{3}{\sqrt{4-x^2}}, & 0 < x < \sqrt{2} \\ \frac{-3}{\sqrt{4-x^2}}, & \sqrt{2} < x < 2 \end{cases}$$

$$\begin{aligned} L &= 4 \left[ \int_0^{\sqrt{2}} \sqrt{1 + \left(\frac{3}{\sqrt{4-x^2}}\right)^2} dx \right] = 4 \int_0^{\sqrt{2}} \sqrt{1 + \frac{9}{4-x^2}} dx \\ &= \int_0^2 \sqrt{16 + \frac{144}{4-x^2}} dx \\ \therefore a &= 16, b = 144 \end{aligned}$$

## 11.11 Areas of Surfaces of Revolution

**Revolution About x-axis** If the region bounded by  $y = f(x)$ , the  $x$ -axis and  $x = a, x = b$  is rotated about the  $x$ -axis, the area of the surface formed is given by:

$$A = 2\pi \int_a^b y \sqrt{1 + \left(\frac{dy}{dx}\right)^2} dx$$

**Revolution About y-axis** If the region bounded by  $x = f(y)$ , the  $y$ -axis and  $y = a, y = b$  is rotated about the  $y$ -axis, the surface area of the surface formed is given by:

$$A = 2\pi \int_a^b x \sqrt{1 + \left(\frac{dx}{dy}\right)^2} dy$$

**Surface Area of Parametrics** Consider a curve defined by  $x = f(t)$  and  $y = g(t)$  for  $a \leq t \leq b$ . If  $P(f(t), g(t))$  traces the curve exactly once from  $t = a$  to  $t = b$  then the area formed by rotating about the  $x$ -axis is given by:

$$A = 2\pi \int_a^b |g(t)| \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt$$

## Total Surface Area of a Solid

$$\Sigma A = A + \pi (f(a))^2 + \pi (f(b))^2$$

For  $A$  being the area of the surface, and  $a, b$  being the limits of the solid of revolution.

## 11.12 Reduction Formulas

### Example: Reduction Formulas Example 1

$$\text{Let } I_n = \int_1^e (\ln(t))^n dt \quad n \in \mathbb{Z}^+$$

i) Show that  $I_n = e - nI_{n-1}$  for  $n \in \mathbb{Z}^+$ .

$$\begin{aligned} I_n &= \int_1^e (\ln(t))^n dt \\ u &= (\ln(t))^n \quad \frac{du}{dt} = \frac{n(\ln(t))^{n-1}}{t} \quad \frac{dv}{dt} = 1 \quad v = t \quad (\text{I.B.P}) \\ I_n &= [t(\ln(t))^n]_1^e - \int_1^e n(\ln(t))^{n-1} dt \\ &= e - n \int_1^e n(\ln(t))^{n-1} dt \\ &= e - nI_{n-1} \text{ As required.} \end{aligned}$$

ii) Hence, or otherwise, find the exact value of  $I_3$ .

$$\begin{aligned} I_3 &= e - 3I_2 \\ &= e - 3(e - 2I_1) = -2e + 6(e - I_0) \\ &= 4e - 6I_0 = 4e - 6 \int_1^e (\ln(t))^0 dt = 4e - [t]_1^e \\ &= 4e - 6(e - 1) = 6 - 2e \end{aligned}$$

## 12 Differential Equations

### 12.1 Tech

#### 12.1.1 deSolve(diffeq,iv,dv)

Press menu+4+D to get this function up. In the diffeq, denote derivatives with an apostrophe, iv is the independent variable and dv is the dependent variable.

#### 12.1.2 euler(dydx,iv,dv,{x0,x1},y0,h)

Input the euler method function. dydx is the derivative of the dependent variable (dv) w.r.t the independent variable (iv). x0 is the x value stipulated in the initial condition, x1 is the maximum x value you wish to enumerate to. y0 is the y value in the initial condition and h is the step size.

### 12.2 Verification of Solutions

We can verify solutions to DiffEqs by substitution.

### 12.3 Proportionality/Inverse Proportionality

#### Exam-style Question: VCAA 2007 Spesh E2 A14

The rate at which a type of bird flu spreads throughout a population of 1000 birds in a certain area is proportional to the product of the number  $N$  of infected birds and the number of birds still **not** infected after  $t$  days. Initially two birds in the population are found to be infected. A differential equation, the solution of which models the number of infected birds after  $t$  days, is

#### My Blunder Solution:

$$\frac{dN}{dt} = k(N - 2)(1000 - N)$$

#### Correct Solution:

$$\frac{dN}{dt} \propto N(1000 - N) \therefore \frac{dN}{dt} = kN(1000 - N)$$

The initial value does not matter in this instance, as it is proportional to the product of the **currently** infected and non-infected birds, not the birds infected **since** the initial measurement.

### 12.4 Logistic DiffEq

$$\frac{dP}{dt} = rP \left(1 - \frac{P}{K}\right)$$

Where  $P$  is the population at time  $t$ ,  $r$  is the 'growth parameter' (rate),  $K$  is the upper limit of the population,  $\frac{dP}{dt} \rightarrow 0$  as  $P \rightarrow K$ . Maximum  $\frac{dP}{dt}$  occurs at  $P = \frac{K}{2}$ .

**General Solution** The general solution to a logistic diffeq  $\frac{dP}{dt}$ :

$$P(t) = \frac{P_0 k}{P_0 + (k - P_0)e^{-rt}} = \frac{P_0 k e^{rt}}{P_0 e^{rt} + (k - P_0)}, \quad P_0 = P(0)$$

#### Exam-style Question: VCAA 2023 Spesh Sample Q2

In a certain region, 500 rare butterflies are released to maintain the species. It is believed that the region can support a maximum of 30 000 such butterflies. The butterfly population  $P$ ,  $t$  years after release can be modelled by the logistic differential equation  $\frac{dP}{dt} = rP \left(1 - \frac{P}{30000}\right)$  where  $r$  is the growth rate of the population.

- a) Use an integration technique and partial fractions to solve the DE above to find  $P$  in terms of  $r$  and  $t$ .
- b) Given that after 10 years there are 1930 butterflies, find  $r$  to 2 decimal places.

a)

$$\begin{aligned}
 r \frac{dt}{dP} &= \frac{1}{P} + \frac{1}{30000 - P} \\
 rt &= \ln(P) - \ln(30000 - P) + c, c \in \mathbb{R} \\
 P(0) = 500 &\implies c = \ln(59) \\
 \therefore rt &= \ln\left(\frac{59P}{30000 - P}\right) \\
 P &= \frac{30000}{1 + 59e^{-rt}}
 \end{aligned}$$

b)

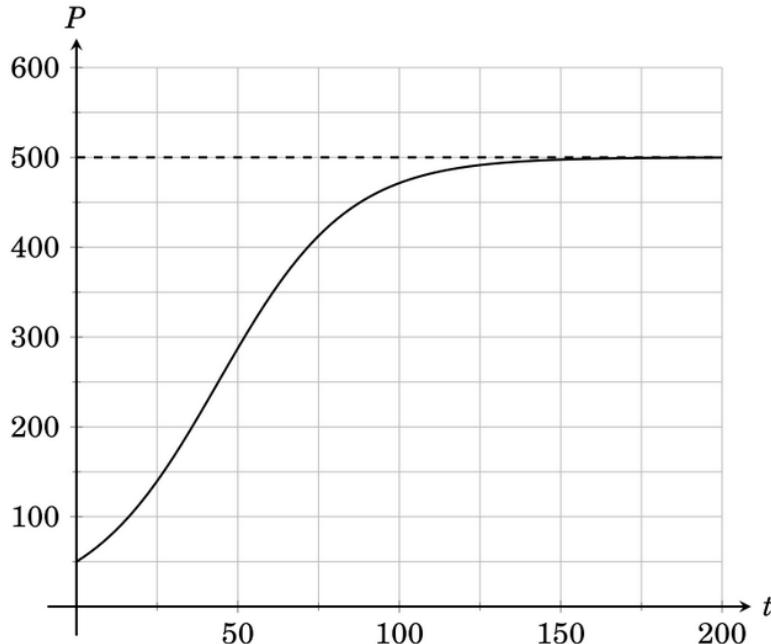
$$\begin{aligned}
 P(10) &= 1930 \\
 r = \frac{1}{t} \ln\left(\frac{59P}{30000 - P}\right) &= \ln\left(\frac{59(1930)}{30000 - 1930}\right) \approx 0.14
 \end{aligned}$$

Exam-style Question: 2023 MAV Spec E2 QA13

### Question 13

The graph below shows the solution curve to the logistic differential equation with solution

$$P(t) = \frac{a}{1 + be^{-\frac{1}{20}t}}, \text{ where } a, b \in \mathbb{R}.$$



The rate of change of  $P$  is greatest when  $t$  is equal to

The asymptote is  $P = 500$  and so  $a = 500$ .

$$P(0) = \frac{500}{1+b} = 50 \implies b = 9$$

Solving  $\frac{500}{1+9e^{-\frac{1}{20}t}} = 50$  gives  $t = 20 \ln(9)$ .

## 12.5 Separation of Variables

$$\frac{dy}{dx} = f(x)g(y) \implies \int f(x)dx = \int \frac{1}{g(y)}dy$$

### 12.5.1 Solving

To solve  $\frac{dy}{dx} = f(x)g(y)$ :

- 1) Write expression clearly as a product of a function in  $x$  and a function in  $y$ .
- 2) Substitute these expressions into the separation of variables form.
- 3) Antidifferentiate both expressions with  $+c$  included (you only need this on one side).

Exam-style Question: 2018 Exam 2 Question A9

A solution to the differential equation  $\frac{dy}{dx} = \frac{2}{\sin(x+y) - \sin(x-y)}$  can be obtained from:

- a)  $\int 1dx = \int 2\sin(y)dy$
- b)  $\int \cos(y)dy = \int \csc(x)dx$

- c)  $\int \cos(x)dx = \int \csc(y)dy$   
d)  $\int \sec(x)dx = \int \sin(y)dy$   
e)  $\int \sec(x)dx = \int \csc(y)dy$

$$\frac{dy}{dx} = \frac{1}{\cos(x)\sin(y)}$$

$$\sin(y)\frac{dy}{dx} = \sec(x)$$

$$\int \sin(y)dy = \int \sec(x)dx \quad (\text{D})$$

## 12.6 DiffEqs + Related Rates Crossover Event

### Example: Inverted Cone

An inverted cone has height  $h$  and radius  $r$ . It is being filled at  $k$  L per minute. The depth of the water is  $x$  at time  $t$  minutes. Construct a diffeq for  $\frac{dx}{dt}$  and solve given the cone was initially empty.

Let  $V$  be the volume of water after  $t$  minutes

$$k \text{ litres} = 1000 \text{ kcm}^3$$

$$\frac{dV}{dt} = 1000k$$

$$\frac{dx}{dt} = \frac{dx}{dV} \times \frac{dV}{dt}$$

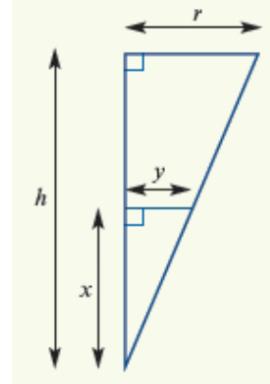
$$V = \frac{1}{3}\pi y^2 x$$

By similar triangles:  $\frac{y}{r} = \frac{x}{h} \implies y = \frac{xr}{h} \implies V = \frac{1}{3}\pi \frac{r^2 x^2}{h^2} x = \frac{\pi r^2}{3h^2} x^3$

$$\therefore \frac{dV}{dx} = \frac{\pi r^2}{h^2} x^2 \implies \frac{dx}{dV} = \frac{h^2}{\pi r^2} \frac{1}{x^2} \therefore \frac{dx}{dt} = \frac{h^2}{\pi r^2 x^2} \times 1000k = \frac{1000kh^2}{\pi r^2 x^2}, k > 0$$

$$\begin{aligned} t &= \int \frac{\pi r^2 x^2}{1000kh^2} dx \\ &= \frac{\pi r^2 x^3}{3000kh^2} + c, c \in \mathbb{R} \end{aligned}$$

Then solve appropriately for  $c$ .



## 12.7 Definite Integration to solve DiffEqs

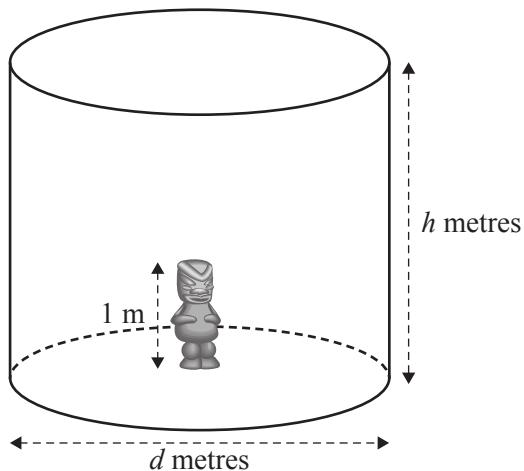
For differential equations  $\frac{dy}{dx} = f(x)$  with  $y_0 = f(x_0)$  being known, the values of  $y$  at  $x_1$  can be found:

$$y(x_1) = \int_{x_0}^{x_1} f(x)dx + y_0$$

**Question 2** (13 marks)

On 1 January 2010, Tasmania Jones was walking through an ice-covered region of Greenland when he found a large ice cylinder that was made a thousand years ago by the Vikings.

A statue was inside the ice cylinder. The statue was 1 m tall and its base was at the centre of the base of the cylinder.



The cylinder had a height of  $h$  metres and a diameter of  $d$  metres. Tasmania Jones found that the volume of the cylinder was  $216 \text{ m}^3$ . At that time, 1 January 2010, the cylinder had not changed in a thousand years. It was exactly as it was when the Vikings made it.

- a. Write an expression for  $h$  in terms of  $d$ .

0 2 marks

$$\begin{aligned} V &= \pi r^2 h \\ 216 &= \pi \left(\frac{d}{2}\right)^2 h \\ h &= \frac{864}{d^2 \pi} \end{aligned}$$

- b. Show that the surface area of the cylinder excluding the base,  $S$  square metres, is given by the rule  $S = \frac{\pi d^2}{4} + \frac{864}{d}$ .

(1 mark)

$$\begin{aligned} S &= 2\pi rh + \pi r^2 \\ &= 2\pi \left(\frac{d}{2}\right) \left(\frac{864}{d^2\pi}\right) + \pi \left(\frac{d}{2}\right)^2 \\ &= \frac{\pi d^2}{4} + \frac{864}{d} \quad \text{as required} \checkmark \end{aligned}$$

Tasmania found that the Vikings made the cylinder so that  $S$  is a minimum.

- c. Find the value of  $d$  for which  $S$  is a minimum and find this minimum value of  $S$ .

(2 marks)

$$\frac{dS}{dd} = \frac{d\pi}{2} - \frac{864}{d^2}$$

$$\text{Let } \frac{d\pi}{2} - \frac{864}{d^2} = 0$$

$$\frac{d\pi}{2} = \frac{864}{d^2} \quad \checkmark$$

$$\Rightarrow d = 12\pi^{-\frac{1}{3}}$$

$$S|_{d=12\pi^{-\frac{1}{3}}} = 108\pi^{\frac{1}{3}} \text{ m}^3 \quad \checkmark$$

- d. Find the value of  $h$  when  $S$  is a minimum.

(1 mark)

$$S \text{ is minimum at } d = 12\pi^{-\frac{1}{3}}$$

$$h = \frac{864}{d^2\pi} = 6\pi^{-\frac{1}{3}} \text{ m} \quad \checkmark$$

On 1 January 2010, Tasmania believed that due to recent temperature changes in Greenland, the ice of the cylinder had just started melting. Therefore, he decided to return on 1 January each year to measure the ice cylinder. He observes that the volume of the ice cylinder decreases by a constant rate of  $10 \text{ m}^3$  per year. Assume that the cylindrical shape is retained and  $d = 2h$  at the beginning and as the cylinder melts.

- e. Write down an expression for  $V$  in terms of  $h$ .

1 mark

$$V = \pi r^2 h$$

$$r = \frac{d}{2} \Rightarrow r = h$$

$$\therefore V = \pi h^3 \quad \checkmark$$

- f. Find  $\frac{dh}{dt}$  in terms of  $h$ .

3 marks

$$\frac{dh}{dt} = \frac{dh}{dV} \cdot \frac{dV}{dt} \quad \checkmark$$

$$V = \pi h^3$$

$$\frac{dV}{dh} = 3\pi h^2$$

$$\frac{dh}{dV} = \frac{1}{3\pi h^2} \quad \checkmark$$

$$\frac{dV}{dt} = -10$$

$$\therefore \frac{dh}{dt} = \frac{-10}{3\pi h^2} \quad \checkmark$$

- g. Find the rate at which the height of the cylinder will be decreasing when the top of the statue is just exposed.

1 mark

$$h = 1$$

$$\left. \frac{dh}{dt} \right|_{h=1} = \frac{-10}{3\pi} \text{ m per year}$$

$\therefore$  decreasing at  $\frac{10}{3\pi} \text{ m per year}$   $\checkmark$

- h. Find the year in which the top of the statue will just be exposed. (Assume that the melting started on 1 January 2010.)

(2 marks)

$$\frac{dt}{dh} = -\frac{3\pi h^2}{10}$$

$$\int \frac{dt}{dh} dh = \int \frac{-3\pi h^2}{10} dh$$

$$t = \int_{-\frac{1}{3}}^1 \frac{-3\pi h^2}{10} dh = 21.2858$$

∴ during 2031 ✓

## 12.8 Newton's Law of Cooling DiffEq

Newton's Law of Cooling involves a DiffEq that describes the rate of change of temperature  $\frac{dT}{dt}$  is proportional to the difference between the temperature and the outside. Note that  $k \in \mathbb{R}^-$  in the below statement.

$$\frac{dT}{dt} \propto (T - T_{external}) \implies \frac{dT}{dt} = k(T - T_{external})$$

## 12.9 Applications of DiffEqs - Concentration Problems

$Q$ =concentration

$$\frac{dQ}{dt} = \frac{dQ_{in}}{dt} - \frac{dQ_{out}}{dt}$$

**In flow:**  $\frac{dQ_{in}}{dt} = \frac{dQ_{in}}{dV_{in}} \times \frac{dV_{in}}{dt}$ .

**In tank:** Mass at any time  $t$ , volume at any time  $t$ , concentration  $C = \frac{\text{mass}}{\text{volume}}$

**Out flow:**  $\frac{dQ_{out}}{dt} = \frac{dQ_{out}}{dV_{out}} \times \frac{dV_{out}}{dt}$ . Out flowing concentration=concentration in tank  $C$ .

### Exam-style Question: 2006 NEAP E1 A21

A 5L container is initially full of fresh water. Saline solution with a concentration of 10g/L flows into the tank at 1L/min. At the same time, the mixture in the container flows out at 2L/min. If  $S$  is the quantity of salt in the container at time  $t$  minutes, write a differential equation describing this situation.

**Into tank:**  $\frac{dQ_{in}}{dt} = 10 \times 1 = 10$

**In tank:**  $C = \frac{S}{5 + (1 - 2)t} = \frac{S}{5 - t}$

**Out of tank:**  $\frac{dQ_{out}}{dt} = \frac{S}{5 - t} \times 2$

Therefore  $\frac{dS}{dt} = \frac{dQ_{in}}{dt} - \frac{dQ_{out}}{dt} = 10 - \frac{2S}{5-t}$

## 12.10 Euler's Method

If  $\frac{dy}{dx} = g(x)$  with  $y = y_0$  when  $x = x_0$ , then:

$$x_{n+1} = x_n + h \quad \text{and} \quad y_{n+1} = y_n + hg(x_n)$$

### Example: Euler's Method Basic Case

Let  $\frac{dy}{dx} = x^2y$  with  $y(1) = 4$ . Apply Euler's method to find  $y_3$  using steps of 0.2.

$$g(x, y) = x^2y, \quad h = 0.2$$

$$0 : \quad x_0 = 1$$

$$y_0 = 4$$

$$1 : \quad x_1 = 1.2$$

$$y_1 = 4 + 0.2(1)^2(4) = 4.8$$

$$2 : \quad x_2 = 1.4$$

$$y_2 = 4.8 + 0.2(1.2)^2(4.8) = 6.18$$

$$3 : \quad x_3 = 1.6$$

$$y_3 = 6.18 + 0.2(1.4)^2(6.18) = 8.606$$

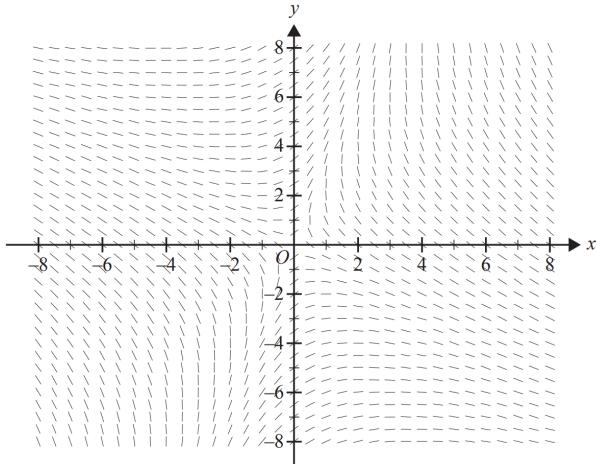
### 12.10.1 Over/Underestimates

If the graph of the solution of a DiffEq is concave up, Euler's Method will produce an underestimate. If the graph of the solution of a DiffEq is concave down, Euler's Method will produce an overestimate.

## 12.11 Slope Fields

### Exam-style Question: 2018 Exam 2 Question A10

The differential equation that best represents the slope field below is



- a)  $\frac{dy}{dx} = \frac{2x+y}{y-2x}$     b)  $\frac{dy}{dx} = \frac{x+2y}{2x-y}$     c)  $\frac{dy}{dx} = \frac{2x-y}{x+2y}$     d)  $\frac{dy}{dx} = \frac{x-2y}{y-2x}$     e)  $\frac{dy}{dx} = \frac{2x+y}{2y-x}$

Plot using **Graphs** page, Menu+3+8 to enter a diffeq. A has the same shape, so A is the answer.

## 12.12 Finding Solutions to DiffEqs

## 13 Pseudocode

### 13.1 Syntax

**Assignment** A variable is a string of one or more letters that acts as a placeholder that can be assigned different values. For example  $x \leftarrow 3$  reads 'assign the value 3 to the variable  $x$ ' or ' $x$  takes the value 3'.

#### Control of Flow of Steps

**If-Then Blocks** This construct provides a means of making decisions within an algorithm. If the condition is true, then the code between the If-Then block and the EndIf statement will execute.

**If** *condition then*

execute these instructions

**End If**

**For loops** Repeated execution of code blocks. Note the convention that 'from 1 to n' is inclusive.

**For** *i From 1 to n*

execute these instructions

**End For**

**While loops** Indefinite repeated iterations of instructions provided some condition remains true.

**While** *condition is true*

execute these instructions

**End While**

**Functions** Functions are sections of pseudocode that can be used to complete a specific task. Once a function is defined it can be used ('called') within another algorithm.

**define** *function\_name(args)*:

execute these instructions

**return** *output*

### 13.2 Example Algorithms

**Example: Newton-Raphson Method to tolerance of 0.001**

```

define newtonraphson(f(x),x0)
    df(x)← f'(x)
    i← 0
    prevx←x0
    While i<1000 do
        nextx←prevx - f(prevx) ÷ df(prevx)
        If 0.001 < nextx - prevx < 0.001 Then
            Return nextx
        Else
            prevx←nextx
            i←i+1
    EndWhile

```

**Example: Numerical Integration with Trapezium Method**

```

define f(x)
    return (function rule)

sum←0
a←lower bound
b←upper bound
n←number of trapeziums
h←(b-a)/n
left←a
right←a+h
for i from 1 to n
    strip← 0.5(f(left)+f(right)) × h
    sum← sum + strip
    left← left + h
    right← right + h
end for
print sum

```

**Example: Estimate of Long-Term Average for Number of Dice Rolls for a Six**

```

sum←0
for i from 1 to 1000
    outcome←0
    count←0
    while outcome ≠ 6
        outcome←randominteger(1,6)
        count←count + 1
    end while
    sum←sum + count
end for
print sum/1000

```

### Example: Bisection Method for x-intercepts

#### Algorithm:

```

define f(x):
    return (function rule)
a $\leftarrow$ lower guess
b $\leftarrow$ upper guess
c $\leftarrow$ (a+b)/2
t $\leftarrow$ tolerance
if f(a)×f(b)>0 then
    print "Incorrect initial estimates"
else
    while b-a>2× t
        if f(a)×f(c)<0 then
            b $\leftarrow$ c
        else
            a $\leftarrow$ c
        end if
        c $\leftarrow$ (a+b)/2
    endwhile
    print c
end if

```

#### Comments:

Function  $f(x)$  is chosen. For example,  $x^2 - 2$ . Good choices for  $a$  and  $b$  are  $a=1$  and  $b=2$  as  $f(1)<0$  and  $f(2)>0$

The **while** loop requires that we continue the iteration until the desired accuracy is reached.

The **if** statement inside the loop ensures that we continue to choose values for which there is a sign difference. For each iteration an average of the new pair is determined.

## 14 Other Tech

### 14.1 Functions

#### 14.1.1 `scriptedmath\poi(f(x),x)`

Gives stationary points, axes intercepts, straight-line asymptotes, and endpoints.

#### 14.1.2 `scriptedmath\inv(f(x),pointX)`

Finds  $f^{-1}(x)$ . If the function is not one-to-one it will restrict domain to contain the point where  $x=pointX$ .

#### 14.1.3 `sam_other\newtonraphson(f,g,e,n)`

Uses the Newton-Raphson method to approximate roots.  $f$  is the function, the roots of which we are trying to estimate.  $g$  is the derivative function.  $e$  is the initial estimate, and  $n$  is the number of iterations.

### 14.2 Parametric Functions

#### 14.2.1 `scriptedmath\pder(vfunc, parameter)`

For a vector function in form  $[x(t)y(t)]$  and parameter  $t$ . This function will find  $\frac{dy}{dx}$ .

## 15 Advanced Maths

### 15.1 The Derivative of $f(x)=4x+1$

This could be a tough one. It might be best to take an indirect approach. Let's start with what we know:

$$f(x) = 4x + 1$$

and make the problem simpler by translating it to a coordinate system I'm going to call "Laplace Space"

$$\mathcal{L}\{f(x)\} = \mathcal{L}\{4x + 1\}$$

Next we should refer to our table of Laplace Transforms, to convert our functions in  $x$  to functions in  $s$ .

$$F(s) = \frac{4}{s^2} + \frac{1}{s} = \frac{s+4}{s^2}$$

Now we're in "Laplace Space". The cool thing about "Laplace Space" is that integration becomes division and differentiation becomes multiplication. To find the derivative, we generally want to multiply everything by  $s$ .

$$sF(s) = \frac{s+4}{s}$$

In "Laplace Space", the derivative of a function is  $sF(s) - f(0)$ .

$$sF(s) - f(0) = \frac{s+4}{s} - (4(0) + 1) = \frac{s+4-s}{s} = \frac{4}{s}$$

The left hand side of our equation is now the version of  $f'(x)$  that exists in "Laplace Space". To find what our derivative is actually equal to, we need to convert everything back to "Cartesian Space"

$$\mathcal{L}^{-1}\{sF(s) - f(0)\} = \mathcal{L}^{-1}\left\{\frac{4}{s}\right\}$$

$$f'(x) = 4$$

And that's our answer,  $f'(x) = 4$ . By taking a detour through "Laplace Space", we were able to treat this like an algebra problem and avoid all of that troublesome, limit-based calculus.

### 15.1.1 Our Table of Laplace Transforms

1	$\frac{1}{s}$
$e^{at}, a \in \mathbb{R}$	$\frac{1}{s-a}$
$t^n, n \in \mathbb{Z}^+$	$\frac{n!}{s^{n+1}}$
$\sqrt{t}$	$\frac{\sqrt{\pi}}{2s^{\frac{3}{2}}}$
$\sin(at), a \in \mathbb{R}$	$\frac{a}{s^2 + a^2}$
$\cos(at), a \in \mathbb{R}$	$\frac{s}{s^2 + a^2}$
$t \sin(at), a \in \mathbb{R}$	$\frac{2as}{(s^2 + a^2)^2}$
$t \cos(at), a \in \mathbb{R}$	$\frac{s^2 - a^2}{(s^2 + a^2)^2}$
$\sin(at) - at \cos(at), a \in \mathbb{R}$	$\frac{2a^3}{(s^2 + a^2)^2}$
$\sin(at) + at \cos(at), a \in \mathbb{R}$	$\frac{2as^2}{(s^2 + a^2)^2}$
$t^n e^{at}, a \in \mathbb{R}, n \in \mathbb{Z}^+$	$\frac{n!}{(s-a)^{n+1}}$

$\cos(at) - at \sin(at), a \in \mathbb{R}$	$\frac{s(s^2 - a^2)}{(s^2 + a^2)^2}$
$\cos(at) + at \sin(at), a \in \mathbb{R}$	$\frac{s(s^2 + 3a^2)}{(s^2 + a^2)^2}$
$\sin(at + b), a, b \in \mathbb{R}$	$\frac{s \sin(b) + a \cos(b)}{s^2 + a^2}$
$\cos(at + b), a, b \in \mathbb{R}$	$\frac{s \cos(b) - a \sin(b)}{s^2 + a^2}$
$\sinh(at), a \in \mathbb{R}$	$\frac{a}{s^2 - a^2}$
$\cosh(at), a \in \mathbb{R}$	$\frac{s}{s^2 - a^2}$
$e^{at} \sin(bt), a, b \in \mathbb{R}$	$\frac{b}{(s-a)^2 + b^2}$
$e^{at} \cos(bt), a, b \in \mathbb{R}$	$\frac{s-a}{(s-a)^2 + b^2}$
$e^{at} \sinh(bt), a, b \in \mathbb{R}$	$\frac{b}{(s-a)^2 - b^2}$
$e^{at} \cosh(bt), a, b \in \mathbb{R}$	$\frac{s-a}{(s-a)^2 - b^2}$
$f(ct), c \in \mathbb{R}$	$\frac{1}{c} F\left(\frac{s}{c}\right)$

Table 1: Laplace Transforms for Equations in  $t$

### 15.2 Sandwich Theorem

Let  $g(x) \leq f(x) \leq h(x)$  for all  $x$  near  $a$  and

$$\lim_{x \rightarrow a} g(x) = \lim_{x \rightarrow a} h(x) = L$$

Then

$$\lim_{x \rightarrow a} f(x) = L$$

The function  $f$  is 'sandwiched' between  $g$  and  $h$ .

**Question 2**

The procedure below has been written in pseudocode.

```

declare integer n
declare integer f
declare integer t1
declare integer t2
set f to 0
set t1 to 2
set t2 to 3
set n to 3
repeat n times
  f = t1 + 2 * t2
  t2 = f
  print f
end loop

```

$f = 2 + 6 = 8$   
 $f = 2 + 16 = 18$   
 $f = 2 + 36 = 38$

The output of the pseudocode is a list of numbers.

The final number in the list is

- A. 3  
 B. 18  
 C. 38  
 D. 72  
 E. 78

**VCE Specialist Mathematics****Written examination 2 – End of year****Sample questions**

These sample questions are intended to demonstrate how new aspects of Units 3 and 4 of VCE Specialist Mathematics may be examined in written examination 2. They do **not** constitute a full examination paper.

**SECTION A – Multiple-choice questions****Question 1**

Consider the following statement.

'For all integers  $n$ , if  $n^2$  is even, then  $n$  is even.'

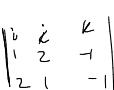
Which one of the following is the **contrapositive** of this statement?

- A. For all integers  $n$ , if  $n^2$  is odd, then  $n$  is odd.  
 B. There exists an integer  $n$  such that  $n^2$  is even and  $n$  is odd.  
 C. There exists an integer  $n$  such that  $n$  is even and  $n^2$  is odd.  
 D. For all integers  $n$ , if  $n$  is odd, then  $n^2$  is odd.  
 E. For all integers  $n$ , if  $n$  is even, then  $n^2$  is even.

$$\neg Q \Rightarrow \neg P$$

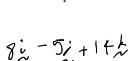
**SM EXAM 2 (SAMPLE)****Question 3**

A vector perpendicular to both of the lines represented by  $\ell_1 = 2\mathbf{i} + 3\mathbf{j} + t(\mathbf{i} + 2\mathbf{j} - \mathbf{k})$  and  $\ell_2 = 3\mathbf{i} + \mathbf{j} - 2\mathbf{k} + t(2\mathbf{i} + \mathbf{j} - \mathbf{k})$  is given by

- A.  $\begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 2 & 3 & 0 \\ 3 & 1 & -2 \end{vmatrix}$   

- B.  $\begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 2 & 3 & 0 \\ 2 & 1 & -1 \end{vmatrix}$
- C.  $\begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 3 & 1 & -2 \\ 2 & 3 & 0 \end{vmatrix}$
- D.  $\begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 3 & 1 & -2 \\ 1 & 2 & -1 \end{vmatrix}$
- E.  $\begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 1 & 2 & -1 \\ 2 & 1 & -1 \end{vmatrix}$

**Question 4**Consider two points with coordinates  $(5, -6, 4)$  and  $(-3, -1, -10)$ .

Which one of the following is the equation of the straight line that passes through these two points?

- A.  $\mathbf{r}(t) = -3\mathbf{i} - \mathbf{j} - 10\mathbf{k} + t(8\mathbf{i} - 5\mathbf{j} + 14\mathbf{k})$   

- B.  $\mathbf{r}(t) = 5\mathbf{i} - 6\mathbf{j} + 4\mathbf{k} + t(3\mathbf{i} + \mathbf{j} + 10\mathbf{k})$
- C.  $\mathbf{r}(t) = -3\mathbf{i} - \mathbf{j} - 10\mathbf{k} + t(5\mathbf{i} - 6\mathbf{j} + 4\mathbf{k})$
- D.  $\mathbf{r}(t) = 5\mathbf{i} - 6\mathbf{j} + 4\mathbf{k} + t(-3\mathbf{i} - \mathbf{j} - 10\mathbf{k})$
- E.  $\mathbf{r}(t) = 8\mathbf{i} - 5\mathbf{j} + 14\mathbf{k} + t(-3\mathbf{i} - \mathbf{j} - 10\mathbf{k})$

**SM EXAM 2 (SAMPLE)****Question 5**

A plane is perpendicular to the vector  $\mathbf{n} = \mathbf{i} - \mathbf{j} + 3\mathbf{k}$  and passes through the point  $(3, 2, -4)$ . The Cartesian equation of this plane is

- A.  $3x + 2y - 4z = -11$   
 B.  $-x + y - 3z = 11$   
 C.  $-3x - 2y + 4z = -11$   
 D.  $x - y + 3z = 11$   
 E.  $x - y + 3z = 3$

$$x - 3z - 11 = 0$$

**Question 6**The shortest distance between the planes given by  $5x - 4y - 12z = 10$  and  $-15x + 12y + 36z = 20$  is

- A. 0  
 B.  $\frac{10}{3\sqrt{185}}$   
 C.  $\frac{10}{\sqrt{185}}$   
 D.  $\frac{50}{3\sqrt{185}}$   
 E.  $\frac{50}{\sqrt{185}}$
- $d_1 = \frac{|5x - 4y - 12z - 10|}{\sqrt{185}}$   
 $d_2 = \frac{|-15x + 12y + 36z - 20|}{\sqrt{185}}$   
 $d_1 - d_2 = \frac{|10\sqrt{185}|}{111} = \frac{50}{\sqrt{185}} = \textcircled{D}$

$$d_1 = \frac{|5x - 4y - 12z - 10|}{\sqrt{185}}$$

$$d_2 = \frac{|-15x + 12y + 36z - 20|}{\sqrt{185}}$$

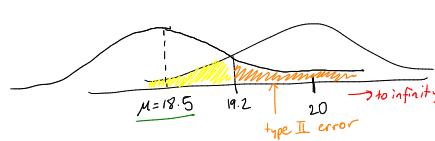
**Question 7**

The time taken by a machine to make electronic components varies normally with a mean of 20 seconds and a standard deviation of 2 seconds. After the machine is serviced, it is believed that the mean time taken has been reduced to 18.5 seconds with the standard deviation remaining the same.

A statistical test is proposed to check whether there is any evidence of a 1.5 second reduction in the mean time taken to make components. The test statistic will be the mean time taken to make a random sample of 16 such components. The type I error for the test will be  $\alpha = 5\%$  with a critical sample mean of 19.2 seconds.

The type II error ( $\beta$ ) for the test is closest to

- A. 8%  
 B. 34%  
 C. 36%  
 D. 46%  
 E. 95%
- $\beta = \text{normCdf}\left(\frac{19.2 - 18.5}{\sqrt{16}}\right) = \text{normCdf}\left(\frac{0.7}{4}\right) = 0.080756711166$

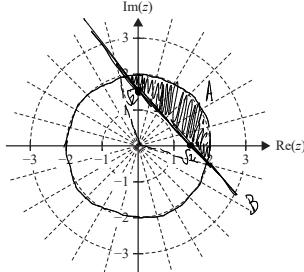


**SECTION B****Question 1 (10 marks)**

- a. Express  $\{z : |z| = |z - 2 \operatorname{cis}\left(\frac{\pi}{4}\right)|, z \in C\}$  in the form  $y = ax + b$ , where  $a, b \in R$ . 2 marks

$$\text{Let } z = x+yi \\ \sqrt{x^2+y^2} = \sqrt{(x-2)^2+(y-2)^2} \\ y = -x + 2\sqrt{2}$$

- b. On the Argand diagram below, sketch and label  $A = \{z : z\bar{z} = 4, z \in C\}$  and sketch and label  $B = \{z : |z| = |z - 2 \operatorname{cis}\left(\frac{\pi}{4}\right)|, z \in C\}$ . Label the axis intercepts of the graph of  $B$ . 3 marks



- c. On the Argand diagram in part b., shade the region defined by  $\{z : z\bar{z} \leq 4, z \in C\} \cap \{z : \operatorname{Re}(z) + \operatorname{Im}(z) \geq \sqrt{2}, z \in C\}$ . 1 mark

- d. Find the area of the shaded region in part c. 2 marks

$$\Theta = 8 \cdot \frac{\pi}{12} = \frac{2\pi}{3} \\ A = 2 \times \left( \frac{2\pi}{3} - \sin\left(\frac{2\pi}{3}\right) \right) = 2 \times \left( \frac{2\pi}{3} - \frac{\sqrt{3}}{2} \right) \\ = \frac{4\pi}{3} - \sqrt{3} \text{ units}^2$$

- e. The elements of  $\{z : z\bar{z} \leq 4, z \in C\} \cap \{z : |z| = |z - 2 \operatorname{cis}\left(\frac{\pi}{4}\right)|, z \in C\}$  provide two of the cube roots of  $w$ , where  $w \in C$ .

Write down all three cube roots of  $w$  in the form  $r\operatorname{cis}(\theta)$  and find  $w$  in the form  $a + ib$ , where  $a, b \in R$ . 2 marks

$$\text{Intersections of circle and line are 2 roots } z_1, z_2 \\ z_1 = 2\operatorname{cis}\left(-\frac{\pi}{12}\right) \quad z_2 = 2\operatorname{cis}\left(\frac{7\pi}{12}\right) \\ \text{poles spaced by } \frac{2\pi}{3} \quad \therefore z_3 = 2\operatorname{cis}\left(\frac{\pi}{12} - \frac{2\pi}{3}\right) = 2\operatorname{cis}\left(-\frac{3\pi}{4}\right) \\ \therefore w = 4\sqrt{2} - 4\sqrt{2}i$$

**Question 2 (10 marks)**

In a certain region, 500 rare butterflies are released to maintain the species.

It is believed that the region can support a maximum of 30 000 such butterflies.

The butterfly population,  $P$ ,  $t$  years after release can be modelled by the logistic differential equation  $\frac{dP}{dt} = rP\left(1 - \frac{P}{30000}\right)$ , where  $r$  is the growth rate of the population.

- a. Use an integration technique and partial fractions to solve the differential equation above to find  $P$  in terms of  $r$  and  $t$ . 3 marks

$$\frac{dP}{dt} = rP\left(1 - \frac{P}{30000}\right) \quad \left| t=0, P=500 \right. \\ \int \frac{1}{P(30000-P)} dP = \int r dt \\ \int \frac{1}{P} + \frac{1}{30000-P} dP = rt \\ \ln(P) - \ln(30000-P) + C = rt \\ \ln\left(\frac{P}{30000-P}\right) + C = rt \\ \frac{P}{30000-P} = e^{rt+C} \\ P = e^{rt+C} \cdot 30000 \\ P = e^{rt} \cdot 30000 e^C \\ P = e^{rt} \cdot 30000$$

- b. Given that after 10 years there are 1930 butterflies in the population, find the value of  $r$  correct to two decimal places. 2 marks

$$1930 = \frac{30000 e^{10r}}{e^{10r} + 59} \\ \Rightarrow r = 0.14$$

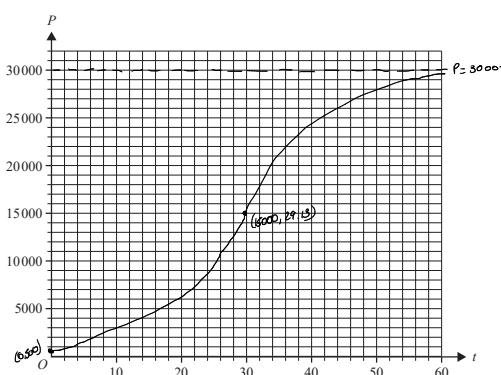
- c. What is the initial rate of increase of the population, correct to one decimal place? 1 mark

$$\frac{dP}{dt} \Big|_{t=0} = 68.9 \text{ butterflies per year}$$

- d. After how many years will the population reach 10 000 butterflies? Give your answer correct to one decimal place. 1 mark

$$t = \frac{1}{r} \ln\left(\frac{59P}{30000-P}\right) = \frac{1}{0.14} \ln\left(\frac{59 \times 10000}{20000}\right) = 24.2 \text{ years}$$

- e. Sketch the graph of  $P$  versus  $t$  on the axes below, showing the value of the vertical intercept. Label the point of fastest population growth as a coordinate pair  $(t, P)$ , with  $t$  labelled correct to two decimal places, and label the asymptote with its equation. 3 marks

**Question 3 (10 marks)**

A plane,  $\Pi_1$ , is described by the parametric equations

$$x = 1 + 2s + 3t \\ y = -2 - s - 2t \\ z = 2 - s + t$$

A second plane,  $\Pi_2$ , contains the point  $P(1, 0, 3)$  and is parallel to the plane  $\Pi_1$ .

- a. Find a vector equation of the plane  $\Pi_1$  in the form  $\underline{r} = \underline{a} + s\underline{b} + t\underline{c}$ . 2 marks

$$\Pi_1: \underline{r} = \underline{i} - 2\underline{j} + 2\underline{k} + s(2\underline{i} - \underline{j} - \underline{k}) + t(3\underline{i} - 2\underline{j} + \underline{k}), \quad s, t \in \mathbb{R}$$

- b. Hence, find a Cartesian equation of the plane  $\Pi_1$ . 2 marks

$$\text{Choose 2 points on } \Pi_1. \text{ Let } \underline{r}_0 = \underline{i} - 2\underline{j} + 2\underline{k} \\ s=1, t=0: \quad \underline{r}_1 = 3\underline{i} - 3\underline{j} + \underline{k} \quad s=0, t=1: \quad \underline{r}_2 = 4\underline{i} - 4\underline{j} + 3\underline{k} \\ \underline{b} = \underline{r}_1 - \underline{r}_0 = 2\underline{i} - \underline{j} - \underline{k}, \quad \underline{c} = \underline{r}_2 - \underline{r}_0 = 3\underline{i} - 2\underline{j} + \underline{k} \\ \underline{a} = \underline{r}_0 - \underline{b} = -3\underline{i} - 5\underline{j} - \underline{k} \quad \therefore \Pi_1: -3x - 5y - z = 5$$

- c. Find a Cartesian equation of the plane  $\Pi_2$ . 1 mark

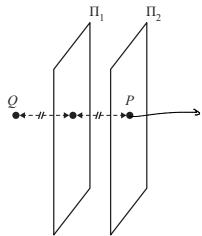
$$\Pi_2: -3x - 5y - z = -6$$

- d. i. Find the shortest distance between the planes  $\Pi_1$  and  $\Pi_2$ .

$$\begin{aligned}\Pi_1: 3x + 5y + z = -5 & \quad \Pi_2: 3x + 5y + z = 6 \\ D_1 = \frac{-5}{\sqrt{3^2 + 5^2 + 1^2}} & \quad D_2 = \frac{6}{\sqrt{3^2 + 5^2 + 1^2}} \\ = \frac{-5}{\sqrt{35}} & \quad = \frac{6}{\sqrt{35}} \\ \therefore \text{shortest distance} &= \frac{|6 - (-5)|}{\sqrt{35}} \text{ units}\end{aligned}$$

2 marks

ii.



Hence, find the coordinates of point  $Q$ , which is the reflection of point  $P$  in the plane  $\Pi_1$ , as shown in the diagram above.

$$\begin{aligned}P(0, 3) & \quad \vec{v} = 3\hat{x} + 5\hat{y} + \hat{z} \\ \vec{r}(t) &= (\hat{x} + 3\hat{y}) + t(3\hat{x} + 5\hat{y} + \hat{z}) \quad \Pi_1: 3x + 5y + z = -5 \\ \vec{r}(t) &= \hat{x} + 3t\hat{y}, \quad y = 5t, \quad z = 3t \\ \therefore 3 + 15t + 5t + 3t &= -5 \\ t &= \frac{-11}{35} \\ \therefore M\left(\frac{2}{35}, \frac{-11}{7}, \frac{94}{35}\right) & \text{ is intersection of line and } \Pi_1 \\ M \text{ is midpoint of } \overline{PQ} & \\ \therefore \frac{1}{2} \left( (\hat{x} + 3\hat{y} + 5\hat{z}) + (\hat{x} + 3\hat{y} + \hat{z}) \right) &= \frac{2}{35}\hat{x} - \frac{11}{7}\hat{y} + \frac{94}{35}\hat{z} \\ \Rightarrow x = \frac{-31}{35}, \quad y = \frac{-22}{7}, \quad z = \frac{83}{35} & \\ \therefore Q\left(\frac{-31}{35}, \frac{-22}{7}, \frac{83}{35}\right) &\end{aligned}$$

3 marks

- Question 4 (10 marks)

- a. Find the shortest distance between the two parallel lines given by

$$\vec{r}(t) = 4\hat{i} + 2\hat{j} + \hat{k} + t(-\hat{i} + \hat{j} + 3\hat{k}), \text{ where } t \in R, \quad \vec{r}(s) = 5\hat{i} + 4\hat{j} - 2\hat{k} + s(-\hat{i} + \hat{j} + 3\hat{k}), \text{ where } s \in R.$$

3 marks

$$\begin{aligned}y &= \sqrt{(-\hat{i} + \hat{j} + 3\hat{k})^2} = \frac{\sqrt{11}}{11}(-\hat{i} + \hat{j} + 3\hat{k}) \\ \ell_1 &= 5\hat{i} + 4\hat{j} - 2\hat{k} \\ \ell_2 &= \hat{i} + 2\hat{j} + 3\hat{k} \\ d &= |\omega| \sin \theta \\ &= |\omega| s \sin \theta \\ &= \frac{3\sqrt{10}}{11} \text{ units}\end{aligned}$$

- b. Given that the lines with equations  $\vec{r}(t) = \hat{i} - 3\hat{j} + 6\hat{k} + (3\hat{i} + 5\hat{j} - a\hat{k})$ , where  $t \in R$ , and  $\vec{r}(s) = -6\hat{i} + 2\hat{j} + \hat{k} + s(4\hat{i} - 10\hat{j} + 6\hat{k})$ , where  $s \in R$ , intersect, find the value of  $a$  and the point of intersection.

4 marks

$$\begin{aligned}\vec{r}(t) &= \vec{r}(s) \\ (13t)\hat{i} + (5t - 3)\hat{j} + (6 - at)\hat{k} &= (4s - 6)\hat{i} + (2 - 10s)\hat{j} + (1 + 6s)\hat{k} \\ 13t - 6 = 0 & \quad 5t - 3 = 2 - 10s \quad ① \\ 6 - at = 1 + 6s & \quad ② \\ \text{solving } ① \text{ and } ② \text{ simultaneously gives } t = 1, s = 1 \\ \text{Sub } t = 1, s = 1 \rightarrow ③ \text{ gives } a = -11 \\ \therefore \vec{r} = -2\hat{i} - 8\hat{j} + 7\hat{k} & \Rightarrow (-2, -8, 7)\end{aligned}$$

- c. The line with equation  $\vec{r}(t) = \hat{i} + \hat{j} - 5\hat{k} + t(4\hat{i} + \hat{j} + 2\hat{k})$ , where  $t, b \in R$ , is parallel to the plane with equation  $2x - 3y - z = 2$ .

Find the value of  $b$  and the shortest distance of the line from the plane.

3 marks

$$\begin{aligned}\vec{n} &= 2\hat{i} - 3\hat{j} - \hat{k} \\ (2\hat{i} - 3\hat{j} - \hat{k}) \cdot (\hat{i} + \hat{j} + 2\hat{k}) &= 0 \\ 8 - 3b - 2 &= 0 \\ b &= 2 \\ \text{shortest dist} &= \frac{|10 \cdot (2 - 5 \cdot 2)|}{\sqrt{1^2 + (-3)^2 + 1^2}} = \frac{2}{\sqrt{14}}\end{aligned}$$

## Question 5 (10 marks)

- a. Given the points  $A(1, 0, 2)$ ,  $B(2, 3, 0)$  and  $C(1, 2, 1)$

- i. find the vector  $\vec{AB} \times \vec{AC}$

$$\vec{AB} \times \vec{AC} = \hat{i} + \hat{j} + 2\hat{k}$$

1 mark

- ii. show that the Cartesian equation of the plane  $\Pi_1$ , containing the points  $A$ ,  $B$  and  $C$ , is  $x + y + 2z = 5$ .

1 mark

$$\vec{n} \cdot \vec{AB} \times \vec{AC} = \hat{i} + \hat{j} + 2\hat{k} \cdot \hat{i} + \hat{j} + 2\hat{k} = 0$$

$$\vec{n} \cdot \vec{AB} = 0$$

$$\vec{n} \cdot (\hat{i} + \hat{j} + 2\hat{k}) = 0 \quad \therefore x + y + 2z = 5 \text{ as required}$$

- b. A second plane,  $\Pi_2$ , has the Cartesian equation  $x - y - z = 0$ .  $L$  is the line of intersection of the planes  $\Pi_1$  and  $\Pi_2$ .

- i. Find the coordinates of the point  $P$ , where  $L$  crosses the  $y$ - $z$  plane.

$$\begin{aligned}\vec{x} - \vec{y} - \vec{z} &= 0 \quad ① \quad x + y + 2z = 5 \quad ② \\ \text{Let } z = \lambda, \quad x = \frac{5-3\lambda}{2}, \quad y = \frac{5-3\lambda}{2}, \quad z = \lambda & \\ x = 0 \Rightarrow \lambda = 5 & \quad \therefore z = 0, y = -5, z = 5 \quad \therefore (0, -5, 5)\end{aligned}$$

- ii. Hence, find the vector equation of the line  $L$ .

$$\begin{aligned}\vec{r}_1: \vec{r}_1 &= \hat{i} + \hat{j} + 2\hat{k} \quad \vec{r}_2: \vec{r}_2 = \hat{i} - \hat{j} - \hat{k} \\ \text{Parallel to } L: \vec{a}_1 \times \vec{a}_2 &= \hat{i} + 2\hat{k} \\ \text{Bmt on } L: (0, -5, 5) & \\ \therefore \vec{r}(\lambda) &= (-5\hat{i} + 5\hat{k}) + \lambda(\hat{i} + 2\hat{k})\end{aligned}$$

- iii. Find the distance from the point  $A$  to the plane  $\Pi_2$ .

$$\begin{aligned}P(0, -5, 5) \text{ on } \Pi_2, \quad \vec{r}_2 &= \hat{i} - \hat{j} - \hat{k} \\ d &= |\vec{AP} \cdot \hat{i}| \\ &= \frac{15}{\sqrt{3}} \text{ units}\end{aligned}$$

- iv. Find the distance from the point  $A$  to the line  $L$ .

$$\begin{aligned}\vec{r}(\lambda) &= \lambda\hat{i} + (3\lambda - 5)\hat{j} + (5 - 2\lambda)\hat{k} \\ \vec{AQ} &= \vec{r}(\lambda) - \vec{OA} = (\lambda - 1)\hat{i} + (3\lambda - 5)\hat{j} + (3 - 2\lambda)\hat{k} \\ \vec{AQ} \cdot \hat{i} &= 0 \quad \rightarrow |\vec{AQ}| \cdot \frac{1}{\sqrt{1+4+9}} = \frac{\sqrt{26}}{7} \text{ units: distance} \\ 14t - 22 &= 0 \\ \therefore t &= \frac{11}{7}\end{aligned}$$

3 marks

**Question 6 (11 marks)**

The position vector  $\mathbf{r}_S(t)$ , from an origin  $O$ , of a sparrow  $t$  seconds after being sighted is modelled by  $\mathbf{r}_S(t) = 23\mathbf{i} + 5t\mathbf{j} + \left(4\sqrt{2}\sin\left(\frac{\pi t}{2}\right) + 4\sqrt{2}\right)\mathbf{k}$ ,  $t \geq 0$ , where  $\mathbf{i}$  is a unit vector in the forward direction,  $\mathbf{j}$  is a unit vector to the left and  $\mathbf{k}$  is a unit vector vertically up. Displacement components are measured in centimetres.

- a. Find the value of  $t$  when the sparrow first lands on the ground. 2 marks

$$\text{Component } \mathbf{k} = 0 : 4\sqrt{2}\sin\left(\frac{\pi t}{2}\right) + 4\sqrt{2} = 0$$

$$t = n-1, n \in \mathbb{Z}$$

First landing at  $t=3$  for  $t \geq 0$

- b. Find the distance of the sparrow from  $O$  when it first lands. Give your answer correct to one decimal place. 2 marks

$$\mathbf{r}_S(3) = 6\mathbf{i} + 15\mathbf{k}$$

$$|\mathbf{r}_S(3)| = 3\sqrt{84} = 70.6 \text{ cm}$$

- c. Find the maximum flight speed, in centimetres per second, of the sparrow. Give your answer correct to one decimal place. 2 marks

$$\dot{\mathbf{r}}_S(t) = 23\mathbf{i} + 5\mathbf{j} + 2\sqrt{2}\pi\cos\left(\frac{\pi t}{2}\right)\mathbf{k}$$

$$|\dot{\mathbf{r}}_S(t)| = \sqrt{2(4\pi^2\cos^2\left(\frac{\pi t}{2}\right) + 27)} \text{ cm s}^{-1}$$

$$\text{Max } |\dot{\mathbf{r}}_S(t)| \text{ occurs at } \cos^2\left(\frac{\pi t}{2}\right) = 1$$

$$\therefore |\dot{\mathbf{r}}_S(t)|_{\max} = 25.2 \text{ cm s}^{-1}$$

A second bird, a miner, flies such that its velocity vector  $\mathbf{v}_M(t)$ , relative to the same origin  $O$ , is modelled by  $\mathbf{v}_M(t) = 6\mathbf{i} + \mathbf{j} + \left(\frac{\pi}{6}\cos\left(\frac{\pi t}{6}\right)\mathbf{k}\right)$ ,  $t \geq 0$ , where velocity components are measured in centimetres per second.

- d. Given that the miner has an initial position vector of  $10\mathbf{i} + 4\mathbf{j} + 4\sqrt{2}\mathbf{k}$ , show that its position

$$\text{vector at time } t \text{ seconds is given by } \mathbf{r}_M(t) = (6t+10)\mathbf{i} + (t+4)\mathbf{j} + \left(\sin\left(\frac{\pi t}{6}\right) + 4\sqrt{2}\right)\mathbf{k}.$$

$$\begin{aligned} \mathbf{r}_M(t) &= \int_0^t \mathbf{v}_M(t) dt = \int_0^t \left[6t\mathbf{i} + \mathbf{j} + \left(\frac{\pi}{6}\cos\left(\frac{\pi t}{6}\right)\mathbf{k}\right)\right] dt \\ &= 6t\mathbf{i} + t\mathbf{j} + \left[\frac{\pi}{6}\sin\left(\frac{\pi t}{6}\right)\mathbf{k}\right] \Big|_0^t \in \mathbb{R}^3 \\ \mathbf{r}_M(0) &= \mathbf{r}_M = 10\mathbf{i} + 4\mathbf{j} + 4\sqrt{2}\mathbf{k} \\ \therefore \mathbf{r}_M(t) &= 6t\mathbf{i} + t\mathbf{j} + \sin\left(\frac{\pi t}{6}\right)\mathbf{k} + 10\mathbf{i} + 4\mathbf{j} + 4\sqrt{2}\mathbf{k} \\ &= (6t+10)\mathbf{i} + (t+4)\mathbf{j} + \left(\sin\left(\frac{\pi t}{6}\right) + 4\sqrt{2}\right)\mathbf{k} \end{aligned}$$

- e. The sparrow and the miner are at the same position at different times.

Find the coordinates of this position and the times at which each bird is at this position.

$$\mathbf{r}_S(\lambda) = \mathbf{r}_M(\gamma), \lambda, \gamma \in \mathbb{R} \Rightarrow 23\lambda = 6\gamma + 10, 5\lambda + 15 = \gamma + 4, \dots$$

$$\Rightarrow \lambda = 2, \gamma = 6$$

$$\mathbf{r}_S(2) = 46\mathbf{i} + 10\mathbf{j} + 4\sqrt{2}\mathbf{k}$$

$$\mathbf{r}_M(6) = 46\mathbf{i} + 10\mathbf{j} + 4\sqrt{2}\mathbf{k}$$

$\therefore P(46, 10, 4\sqrt{2})$  is the position

Sparrow at  $P$  at 2 seconds Miner at  $P$  at 6 seconds

## 16 Cheeky Snack