



The  
University  
Of  
Sheffield.

**MAS140**

**SCHOOL OF MATHEMATICS AND STATISTICS**

**Spring Semester  
2017–2018**

**MAS140 Mathematics (Chemical)**

**3 hours**

*Attempt **ALL** the questions.*

*Each question in Section A carries 3 marks,  
each question in Section B carries 8 marks.*

*All solutions should be justified in full. Calculators should be relied upon for simple steps like basic arithmetic and plugging numbers into elementary functions.*

### Section A

**A1** Let  $f(x) = \frac{3x+2}{3-x} + 2$ . State the domain of  $f(x)$ . Find  $f^{-1}(x)$  and give the domain of  $f^{-1}(x)$ .

**A2** Find  $\frac{d}{dx} \left( \frac{x^2 e^x}{x+1} \right)$ .

**A3** Evaluate

$$\lim_{x \rightarrow 0} \frac{x - \sin x}{x - \tan x}$$

by using Maclaurin series expansions, or l'Hospital's Rule.

**A4** Derive Euler's formula

$$e^{ix} = \cos x + i \sin x$$

by using Taylor series expansions.

**A5** Find the locus of the complex numbers  $z$  that satisfy  $|z + 2i - 3| = |z + 3i|$ . Find also the complex number that lies on this locus and has  $\arg z = \pi/4$ .

**A6** Determine  $a$  and  $b$  such that

$$(ai + bj + k) \times (2i + 2j + 3k) = i - j$$

holds, where  $i, j, k$  denote the standard unit vectors.

**A7** Find the indefinite integral  $\int \sqrt{x^2 - 9} dx$  by the substitution  $x = 3 \cosh u$ .

**A8** Find the indefinite integral  $\int \frac{dx}{x \ln x}$  by using a suitable substitution.

**A9** Solve the following system of equations

$$\begin{cases} x - y + z = 0, \\ 3x + y - 4z = 0, \\ 5x - y - 2z = 0. \end{cases}$$

**A10** Find and classify the stationary points of  $f(x, y) = 3x^2 + xy + 2y$ .

**A11** Let  $A = \begin{pmatrix} 1 & 2 & 0 \\ 3 & -1 & 4 \end{pmatrix}$ . Find  $A^T A$  and  $AA^T$ , if it is possible to define either or both. Here  $A^T$  denotes the transpose of matrix  $A$ .

**A12** Find the general solution of

$$\frac{d^2y}{dx^2} + \frac{dy}{dx} + y = 0.$$

## Section B

**B1** (i) Consider the definite integrals

$$I = \int_0^{\pi/2} \frac{\sin x}{\sin x + \cos x} dx, \quad J = \int_0^{\pi/2} \frac{\cos x}{\sin x + \cos x} dx.$$

Show that  $J - I = 0$ .

(ii) Compute  $I + J$ , hence evaluate  $I$ .

**B2** Consider the following differential equation

$$\frac{dy}{dt} + y = e^{-at},$$

where  $a$  is a constant and  $y(0) = 0$ .

(i) Solve it for  $a \neq 1$ .

(ii) By taking the limit  $a \rightarrow 1$ , or otherwise, solve it for  $a = 1$ .

**B3** Let  $A = \begin{pmatrix} 6 & -3 & -7 \\ -1 & 2 & 1 \\ 5 & -3 & -6 \end{pmatrix}$ . Find all the eigenvalues of  $A$  and the corresponding eigenvectors.

**B4** (i) Show that the Laplace transform  $F(s)$  of  $f(t) = \frac{\sin t}{t}$  satisfies

$$F'(s) = -\frac{1}{s^2 + 1}.$$

(ii) Derive

$$F(s) = -\tan^{-1} s + \frac{\pi}{2}$$

and hence show that

$$\int_0^{\infty} \frac{\sin t}{t} dt = \frac{\pi}{2}.$$

**B5** The position vector  $\mathbf{r}(t)$  of a particle is given by

$$\mathbf{r}(t) = 2(\cos t)\mathbf{i} + 2(\sin t)\mathbf{j} + e^{-t}\mathbf{k},$$

where  $\mathbf{i}, \mathbf{j}, \mathbf{k}$  are the standard unit vectors.

- (i) Find the velocity  $\mathbf{v} = \frac{d\mathbf{r}}{dt}$  and the acceleration  $\mathbf{a} = \frac{d^2\mathbf{r}}{dt^2}$  at time  $t$ .
- (ii) When  $t = 0$ , find a unit vector  $\mathbf{t}$  in the direction of  $\mathbf{v}$ . Also, find the tangential component of  $\mathbf{a}$  in the direction of  $\mathbf{v}$ .

**B6** (i) By differentiating the right-hand side, or otherwise, show that

$$\int \frac{dx}{(1+x^2)^{3/2}} = \frac{x}{(1+x^2)^{1/2}} + C$$

holds.

- (ii) Solve the linear differential equation

$$(1+x^2)\frac{dy}{dx} = xy + 1.$$

Hint: You may make use of (i).

**B7** Show that

$$e^x \cos x = \sum_{n=0}^{\infty} \frac{2^{n/2} \cos \frac{n\pi}{4}}{n!} x^n.$$

Hint: By  $\cos x = \operatorname{Re}(e^{ix})$ , we may regard the left-hand side as the real part of a complex function.

**B8** Using Gaussian elimination, or otherwise, solve the following system of linear equations

$$\begin{cases} 2x - y + 3z = -3, \\ x + 2y - 2z = 7, \\ 4x + 3y + z = 9. \end{cases}$$

**End of Question Paper**

MAS140/151/152/156/161 Formula Sheet

These results may be quoted without proof unless proofs are asked for in the questions.

Trigonometry

$$\sin^2 x + \cos^2 x = 1$$

$$1 + \tan^2 x = \sec^2 x$$

$$1 + \cot^2 x = \operatorname{cosec}^2 x$$

$$2 \sin^2 x = 1 - \cos 2x$$

$$2 \cos^2 x = 1 + \cos 2x$$

$$2 \sin x \cos x = \sin 2x$$

$$\cos(x \pm y) = \cos x \cos y \mp \sin x \sin y$$

$$\sin(x \pm y) = \sin x \cos y \pm \cos x \sin y$$

$$\tan(x \pm y) = \frac{\tan x \pm \tan y}{1 \mp \tan x \tan y}$$

$$a \cos x + b \sin x = R \cos(x - \alpha)$$

$$\text{where } R = \sqrt{a^2 + b^2},$$

$$\cos \alpha = \frac{a}{R} \quad \text{and} \quad \sin \alpha = \frac{b}{R}$$

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

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

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

$$\cos x = \frac{1 - \tan^2(x/2)}{1 + \tan^2(x/2)}$$

$$\sin x = \frac{2 \tan(x/2)}{1 + \tan^2(x/2)}$$

$$\tan x = \frac{2 \tan(x/2)}{1 - \tan^2(x/2)}$$

Hyperbolic Functions

$$\sinh x = \frac{1}{2}(e^x - e^{-x})$$

$$\cosh x = \frac{1}{2}(e^x + e^{-x})$$

$$\tanh x = \frac{\sinh x}{\cosh x}$$

$$\operatorname{coth} x = \frac{\cosh x}{\sinh x}$$

$$\operatorname{sech} x = \frac{1}{\cosh x}$$

$$\cosh^2 x - \sinh^2 x = 1$$

$$2 \cosh^2 x = 1 + \cosh 2x$$

$$2 \sinh^2 x = \cosh 2x - 1$$

$$2 \sinh x \cosh x = \sinh 2x$$

$$\operatorname{sech}^2 x = 1 - \tanh^2 x$$

$$\sinh^{-1} x = \ln(x + \sqrt{x^2 + 1}), \text{ all } x$$

$$\cosh^{-1} x = \ln(x + \sqrt{x^2 - 1}), \quad x \geq 1$$

$$\tanh^{-1} x = \frac{1}{2} \ln \left( \frac{1+x}{1-x} \right), \quad |x| < 1$$

## Series

Sum of an arithmetic series:

$$\frac{\text{first term} + \text{last term}}{2} \times (\text{number of terms})$$

Sum of a geometric series:  $1 + x + x^2 + \dots + x^{n-1} = \frac{1 - x^n}{1 - x}$

Binomial theorem:  $(1 + x)^n = 1 + nx + \frac{n(n-1)}{2!}x^2 + \dots + \binom{n}{r}x^r + \dots$

$$\text{where } \binom{n}{r} = \frac{n(n-1)(n-2)\dots(n-r+1)}{r!}$$

If  $n$  is a positive integer then the series terminates and the result is true for all  $x$ , otherwise, the series is infinite and only converges for  $|x| < 1$ .

$$\left. \begin{aligned} \sin x &= x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \dots \\ \cos x &= 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \dots \\ \sinh x &= x + \frac{x^3}{3!} + \frac{x^5}{5!} + \frac{x^7}{7!} + \dots \\ \cosh x &= 1 + \frac{x^2}{2!} + \frac{x^4}{4!} + \frac{x^6}{6!} + \dots \\ \exp x &= e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots \end{aligned} \right\} \text{valid for all } x$$
$$\ln(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \dots \quad (-1 < x \leq 1)$$

## Differentiation

<u>Function</u>	<u>Derivative</u>	<u>Function</u>	<u>Derivative</u>
$\sin x$	$\cos x$	$\cos x$	$-\sin x$
$\tan x$	$\sec^2 x$	$\cot x$	$-\operatorname{cosec}^2 x$
$\sin^{-1} x$	$\frac{1}{\sqrt{1-x^2}},  x  < 1$	$\cos^{-1} x$	$-\frac{1}{\sqrt{1-x^2}},  x  < 1$
$\tan^{-1} x$	$\frac{1}{1+x^2}$	$\cot^{-1} x$	$-\frac{1}{1+x^2}$
$\sinh x$	$\cosh x$	$\cosh x$	$\sinh x$
$\tanh x$	$\frac{1}{\cosh^2 x}$	$\coth x$	$-\frac{1}{\sinh^2 x}$
$\sinh^{-1} x$	$\frac{1}{\sqrt{x^2+1}}$	$\cosh^{-1} x$	$\frac{1}{\sqrt{x^2-1}},  x  > 1$
$\tanh^{-1} x$	$\frac{1}{1-x^2},  x  < 1$		
$\coth^{-1} x$	$\frac{1}{1-x^2},  x  > 1$		

## Integration

In the following table the constants of integration have been omitted.

$$\int x^n dx = \frac{x^{n+1}}{n+1} \quad (n \neq -1)$$

$$\int \frac{dx}{x} = \ln |x|$$

$$\int e^x dx = e^x$$

$$\int a^x dx = \frac{a^x}{\ln a} \quad (a > 0, a \neq 1)$$

$$\int \sin x dx = -\cos x$$

$$\int \cos x dx = \sin x$$

$$\int \sec^2 x dx = \tan x$$

$$\int \operatorname{cosec}^2 x dx = -\cot x$$

$$\int \sinh x dx = \cosh x$$

$$\int \cosh x dx = \sinh x$$

$$\int \operatorname{sech}^2 x dx = \tanh x$$

$$\int \operatorname{cosech}^2 x dx = -\operatorname{coth} x$$

$$\int \frac{dx}{\sqrt{a^2 - x^2}} = \sin^{-1} \frac{x}{a} \quad (|x| < a)$$

$$\int \frac{dx}{a^2 + x^2} = \frac{1}{a} \tan^{-1} \frac{x}{a}$$

$$\int \frac{dx}{\sqrt{x^2 + a^2}} = \sinh^{-1} \frac{x}{a}$$

$$\int \frac{dx}{\sqrt{x^2 - a^2}} = \cosh^{-1} \frac{x}{a} \quad (|x| > a)$$

$$\int \frac{dx}{a^2 - x^2} = \frac{1}{2a} \ln \left| \frac{a+x}{a-x} \right| \quad \left( = \frac{1}{a} \tanh^{-1} \frac{x}{a} \quad \text{if } |x| < a \right)$$

$$\int \operatorname{cosec} x dx = \ln \tan \left( \frac{x}{2} \right) \quad \text{or} \quad \ln (\operatorname{cosec} x - \cot x)$$

$$\int \sec x dx = \ln \tan \left( \frac{x}{2} + \frac{\pi}{4} \right) \quad \text{or} \quad \ln (\sec x + \tan x)$$

$$\int \operatorname{cosech} x dx = \ln \tanh \left( \frac{x}{2} \right)$$



### Integration by parts

$$\int f(x) g'(x) dx = f(x) g(x) - \int f'(x) g(x) dx$$

### Variable substitution in definite integral

If  $x = \varphi(t)$  is a monotonic function in the interval  $[\alpha, \beta]$  and  $a = \varphi(\alpha)$ ,  $b = \varphi(\beta)$ , then

$$\int_a^b f(x) dx = \int_\alpha^\beta f(\varphi(t)) \varphi'(t) dt$$

### Variable substitution for a rational function of $\sin x$ and $\cos x$

Let  $t = \tan\left(\frac{x}{2}\right)$  then  $\sin x = \frac{2t}{1+t^2}$ ,  $\cos x = \frac{1-t^2}{1+t^2}$  and  $\frac{dx}{dt} = \frac{2}{1+t^2}$ .

### Table of Laplace transforms

<u>Function <math>f(t)</math></u>	<u>Laplace transform <math>F(s)</math></u>
$t^n$	$\frac{n!}{s^{n+1}}$ (for $n = 0, 1, 2, \dots$ )
$e^{at}$	$\frac{1}{s-a}$
$\sin \omega t$	$\frac{\omega}{s^2 + \omega^2}$
$\cos \omega t$	$\frac{s}{s^2 + \omega^2}$
$\sinh \omega t$	$\frac{\omega}{s^2 - \omega^2}$
$\cosh \omega t$	$\frac{s}{s^2 - \omega^2}$
$e^{at} f(t)$	$F(s-a)$ (shift theorem)
$f'(t)$	$sF(s) - f(0)$
$f''(t)$	$s^2 F(s) - sf(0) - f'(0)$