

About the HELM Project

HELM (Helping Engineers Learn Mathematics) materials were the outcome of a three-year curriculum development project undertaken by a consortium of five English universities led by Loughborough University, funded by the Higher Education Funding Council for England under the Fund for the Development of Teaching and Learning for the period October 2002–September 2005.

HELM aims to enhance the mathematical education of engineering undergraduates through a range of flexible learning resources in the form of Workbooks and web-delivered interactive segments.

HELM supports two CAA regimes: an integrated web-delivered implementation and a CD-based version.

HELM learning resources have been produced primarily by teams of writers at six universities: Hull, Loughborough, Manchester, Newcastle, Reading, Sunderland.

HELM gratefully acknowledges the valuable support of colleagues at the following universities and colleges involved in the critical reading, trialling, enhancement and revision of the learning materials: Aston, Bournemouth & Poole College, Cambridge, City, Glamorgan, Glasgow, Glasgow Caledonian, Glenrothes Institute of Applied Technology, Harper Adams University College, Hertfordshire, Leicester, Liverpool, London Metropolitan, Moray College, Northumbria, Nottingham, Nottingham Trent, Oxford Brookes, Plymouth, Portsmouth, Queens Belfast, Robert Gordon, Royal Forest of Dean College, Salford, Sligo Institute of Technology, Southampton, Southampton Institute, Surrey, Teesside, Ulster, University of Wales Institute Cardiff, West Kingsway College (London), West Notts College.

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HELM Workbooks List

1	Basic Algebra	26	Functions of a Complex Variable
2	Basic Functions	27	Multiple Integration
3	Equations, Inequalities & Partial Fractions	28	Differential Vector Calculus
4	Trigonometry	29	Integral Vector Calculus
5	Functions and Modelling	30	Introduction to Numerical Methods
6	Exponential and Logarithmic Functions	31	Numerical Methods of Approximation
7	Matrices	32	Numerical Initial Value Problems
8	Matrix Solution of Equations	33	Numerical Boundary Value Problems
9	Vectors	34	Modelling Motion
10	Complex Numbers	35	Sets and Probability
11	Differentiation	36	Descriptive Statistics
12	Applications of Differentiation	37	Discrete Probability Distributions
13	Integration	38	Continuous Probability Distributions
14	Applications of Integration 1	39	The Normal Distribution
15	Applications of Integration 2	40	Sampling Distributions and Estimation
16	Sequences and Series	41	Hypothesis Testing
17	Conics and Polar Coordinates	42	Goodness of Fit and Contingency Tables
18	Functions of Several Variables	43	Regression and Correlation
19	Differential Equations	44	Analysis of Variance
20	Laplace Transforms	45	Non-parametric Statistics
21	z -Transforms	46	Reliability and Quality Control
22	Eigenvalues and Eigenvectors	47	Mathematics and Physics Miscellany
23	Fourier Series	48	Engineering Case Studies
24	Fourier Transforms	49	Student's Guide
25	Partial Differential Equations	50	Tutor's Guide

Student's Guide

49.1	Introduction to HELM	2
49.2	HELM Workbooks	5
49.3	HELM Electronic Learning Resources	11
49.4	General Advice to Students Studying Mathematics	16
49.5	Some Useful Websites	28
49.6	List of Sections in Workbooks 1 to 48	29
49.7	Index of Engineering Contexts in Workbooks 1 to 48	36
49.8	Mathematics Facts and Formulae	46

Introduction

49.1

1. Background to the HELM project

In 1997, funding was made available by Loughborough University for the 'Open Learning Project' in Mathematics for Engineers which provided high-quality student-centred workbooks, computer aided learning material closely allied to the workbooks, and a strategy for computer aided assessment which can be used for self-assessment and for module assessment. For students following this open learning regime, lectures are now optional as they can now choose to study, with guidance, the mathematics independently.

The success of the Open Learning Project encouraged staff to seek funding to develop further this work resulting in the HELM project which was supported by a £250,000 HEFCE FDTL4 grant for the period Oct 2002-Sept 2005, with the ultimate aim to make high quality materials available throughout Higher Education Institutions in England and Northern Ireland.

2. The HELM project

The HELM team comprised staff at Loughborough University and four consortium partners in other English universities: Hull, Manchester, Reading and Sunderland. The project's aims were to considerably enhance, extend and thoroughly test Loughborough's original Open Learning materials. These were to be achieved mainly by the writing of additional Workbooks and incorporating engineering examples and case studies closely related to the mathematics presented, enhancing the question data-banks, upgrading the Interactive Learning Resources and adding some more for basic mathematics topics, and promoting widespread trialling.

The HELM project's output consists of Workbooks, Interactive Learning segments and linked Revision Tests, and a Computer Aided Assessment regime which is used to help 'drive the student learning', a Student's Guide and a Tutor's Guide.

The Workbooks may be integrated into existing engineering degree programmes either by selecting isolated stand-alone units to complement other materials or by creating a complete scheme of work for a semester or year or two years by selecting from the large set of Workbooks available. These may be used to support lectures or for independent learning.

HELM's emphasis is on flexibility - the work can be undertaken as private study, distance learning or can be teacher-led, or a combination, according to the learning style and competence of the student and the approach of the particular lecturer.

3. HELM project Workbooks

50 Workbooks are available which comprise:

- 46 Student Workbooks written specifically with the typical engineering student in mind containing mathematical and statistical topics, worked examples, tasks and related engineering examples.
- A Workbook containing supplementary mathematical topics and physics case studies.
- A Workbook containing Engineering Case Studies ranging over many engineering disciplines.
- A Students' Guide (this document)
- A Tutor's Guide

The main project materials are the Workbooks which are subdivided into manageable Sections. As far as possible, each Section is designed to be a self-contained piece of work that can be attempted by the student in a few hours. In general, a whole Workbook typically represents 2 to 3 weeks' work. Each Workbook Section begins with statements of prerequisites and the desired learning outcomes.

The Workbooks include (a) worked examples, (b) tasks for students to undertake with space for students to attempt the questions, and, often, intermediate results provided to guide them through problems in stages, and (c) exercises where normally only the answer is given.

4. HELM project Interactive Learning Resources

The project has 80 Interactive Learning Resources, which link to most of the lower level Mathematics and Statistics Workbooks. These enable web-based versions of the Workbooks to contain some audio and some simple animations. Revision exercises with randomly generated questions are provided for the benefit of students working independently.

5. HELM project Assessment Regime

The HELM assessment strategy is based on using Computer-Aided Assessment (CAA) to encourage self-assessment to verify that the appropriate skills have been learned. The project's philosophy is that assessment should be at the heart of any learning and teaching strategy and Loughborough University's own implementation of HELM makes extensive use of CAA to support the students' learning.

HELM provides an integrated web-delivered CAA regime for both self-testing and formal assessment, with around 5000 questions, most have a page of specific feedback.

6. HELM Consortium and Triallist Institutions and Individual Contributors

HELM learning resources have been produced primarily by a consortium of writers and developers at five universities:

Hull, Loughborough, Manchester, Reading, Sunderland.

The HELM consortium gratefully acknowledges the valuable support of many colleagues at their own institutions and at the following institutions involved in additional writing, critical reading, trialling and revising of the learning materials.

Universities
Aston
Cambridge
City
Glamorgan
Glasgow
Glasgow Caledonian
Hertfordshire
Leicester
Liverpool
London Metropolitan
Newcastle
Northumbria
Nottingham
Nottingham Trent
Oxford Brookes
Plymouth
Queen's Belfast
Robert Gordon
Southampton
Southampton Solent
Surrey
Teesside
Ulster
University of Wales Institute Cardiff

Other HE/FE Institutions
Bournemouth & Poole College
Glenrothes Institute of Applied Technology
Harper Adams University College
Moray College
Royal Forest of Dean College
Sligo Institute of Technology
Westminster Kingsway College
West Notts College

HELM Workbooks

49.2

1. List of Workbooks

No.	Title	Pages
1	Basic Algebra	89
2	Basic Functions	75
3	Equations, Inequalities & Partial Fractions	71
4	Trigonometry	77
5	Functions and Modelling	49
6	Exponential and Logarithmic Functions	73
7	Matrices	50
8	Matrix Solution of Equations	32
9	Vectors	66
10	Complex Numbers	34
11	Differentiation	58
12	Applications of Differentiation	63
13	Integration	62
14	Applications of Integration 1	34
15	Applications of Integration 2	31
16	Sequences and Series	51
17	Conics and Polar Coordinates	43
18	Functions of Several Variables	40
19	Differential Equations	70
20	Laplace Transforms	73
21	z -Transforms	96
22	Eigenvalues and Eigenvectors	53
23	Fourier Series	73
24	Fourier Transforms	37
25	Partial Differential Equations	42
26	Functions of a Complex Variable	58
27	Multiple Integration	83
28	Differential Vector Calculus	53
29	Integral Vector Calculus	77
30	Introduction to Numerical Methods	64
31	Numerical Methods of Approximation	86
32	Numerical Initial Value Problems	80
33	Numerical Boundary Value Problems	36
34	Modelling Motion	63
35	Sets and Probability	53
36	Descriptive Statistics	45

No.	Title	Pages
37	Discrete Probability Distributions	60
38	Continuous Probability Distributions	27
39	The Normal Distribution	39
40	Sampling Distributions and Estimation	22
41	Hypothesis Testing	42
42	Goodness of Fit and Contingency Tables	24
43	Regression and Correlation	32
44	Analysis of Variance	57
45	Non-parametric Statistics	36
46	Reliability and Quality Control	38
47	Mathematics and Physics Miscellany	70
48	Engineering Case Studies	97
49	Student's Guide	57
50	Tutor's Guide	143

2. Nomenclature used for problems

- **Examples** are problems with fully worked solutions.
- **Engineering Examples** (found in most Mathematics Workbooks but not the Statistics Workbooks) are problems with an engineering context having fully worked solutions.
- **Tasks** are problems with spaces for the student's working, followed by fully worked solutions. Many Tasks are often broken up into stages with the answer to a stage given before the next stage is reached. [Note: Some tutors may provide workbooks without these worked solutions.]
- **Exercises** are problems for the student to do without spaces provided for the student's working. In general they do not have fully worked solutions, merely answers, but exceptions are: Numerical Workbooks 30-33 and Statistics Workbooks 35-46 which do have fully worked solutions.

3. Notation used

In general HELM uses italic serif font letters (e.g. $f(x)$) to represent functions, variables and constants. However, as exceptions HELM Workbooks use the following non-italic sans-serif letters:

Mathematics

e for the exponential constant and for the exponential function (primarily use in introductory Workbook 6, elsewhere e is often used)

i where $i^2 = -1$

\ln for natural logarithm

Statistics

E for Expectation

P for Probability

V for Variance

M for Median

Complex numbers

HELM uses i rather than j to represent $\sqrt{-1}$ so $i^2 = -1$, although there are one or two exceptions to this (in Workbook 48: Engineering Case Studies).

Vectors

HELM uses underlining of vectors rather than using bold e.g. a

HELM uses \hat{n} for the unit normal vector but does not put the $\hat{}$ on the basic unit vectors in the x, y and z directions which have the standard symbols i , j , k .

Identities

Although HELM introduces and uses the identity symbol ' \equiv ' extensively in Workbook 1: Basic Algebra and in Workbook 4: Trigonometry it is not normally used elsewhere and the more normal '=' is used except where emphasis seems advisable. (HELM is therefore not consistent.)

4. Description of HELM Workbook layout

On the following three pages are reproduced from the electronic Student's Guide explanatory pages concerning Workbook Layout.

Complex Arithmetic

10.1

Introduction

Complex numbers are used in many areas of engineering and science. In this Section we define what a complex number is and explore how two such numbers may be combined together by adding, subtracting, multiplying and dividing. We also show how to find 'complex roots' of polynomial equations.

A **complex number** is a generalisation of an ordinary real number. In fact, as we shall see, a complex number is a pair of real numbers ordered in a particular way. Fundamental to the study of complex numbers is the symbol i with the strange looking property $i^2 = -1$. Apart from this property complex numbers follow the usual rules of number algebra.

Workbook introduction.

What you should learn.

What you should know before you start.



Prerequisites

Before starting this Section you should ...

- be able to add, subtract, multiply and divide real numbers
- be able to combine algebraic fractions together
- understand what a polynomial is
- have a knowledge of trigonometric identities



Learning Outcomes

On completion you should be able to ...

- combine complex numbers together
- find the modulus and conjugate of a complex number
- obtain complex solutions to polynomial equations

Key Points.
Take especial note of these.



Key Point 1

The symbol i is such that

$$i^2 = -1$$

Using the normal rules of algebra it follows that

$$i^3 = i^2 \times i = -i \quad i^4 = i^2 \times i^2 = (-1) \times (-1) = 1$$

and so on.

Task for you to try with space for your working.
Answer presented after solution box.



If $z = -2 + i$ and $w = 3 + 2i$ find expressions for

(a) $z + 2w$, (b) $|z - w|$ and (c) zw

Your solution

(a)

Answer

$$z + 2w = 4 + 5i$$

Your solution

(b) Hint: you should find that $z - w = -5 - i$

Answer

$$|z - w| = \sqrt{(-5)^2 + (-1)^2} = \sqrt{26}$$

Your solution

(c)

Answer

$$zw = -6 + 3i - 4i + 2i^2 = -8 - i$$

Worked example.
Solution with explanation follows in box.



Example 2

Find $\frac{z}{w}$ if $z = 2 - 3i$ and $w = 2 + i$.

Solution

$$\begin{aligned}\frac{z}{w} = \frac{2 - 3i}{2 + i} &= \frac{(2 - 3i) \times (2 - i)}{(2 + i) \times (2 - i)} && \text{rationalising} \\ &= \frac{4 - 3 + i(-6 - 2)}{4 + 1} && \text{multiplying out} \\ &= \frac{1}{5} - \frac{8}{5}i && \text{dividing through}\end{aligned}$$

Exercise for you to do.
Answers follow in box (usually no detailed solution).

Exercises

1. Find the roots of the equation $x^2 + 2x + 2 = 0$.
2. If i is one root of the cubic equation $x^3 + 2x^2 + x + 2 = 0$ find the two other roots.
3. Find the complex number z if $2z + z^* + 3i + 2 = 0$.
4. If $z = \cos \theta + i \sin \theta$ show that $\frac{z}{z^*} = \cos 2\theta + i \sin 2\theta$.

Answers 1. $x = -1 \pm i$ 2. $-i, -2$ 3. $-\frac{2}{3} - 3i$

HELM Electronic Learning Resources

49.3

1. Introduction

HELM has 50 Workbooks and 80 Interactive Learning Resources and linked Revision Questions (with inbuilt randomisation).

The Interactive Learning Resources provide web-based lessons to match some Sections of many of the more elementary Workbooks and contain animations and interactivity to generate interest and have linked Revision Exercises where randomly generated questions are provided for the benefit of students working independently.

These Interactive Learning Resources and linked Revision Exercises have been found to be especially useful for supporting students who find it difficult to cope with the mathematical demands of their programmes.

The animations are also useful for illustrating lectures and for revision.

The tutor will provide guidance as to how the materials are to be used.

2. Accessing HELM electronic learning resources

The web based versions of HELM Interactive Learning Resources can be accessed via

<http://helm.lboro.ac.uk/cal/>

or via any specific web address (url) given to you by your tutor.

Once you access this web page, you will see four links as shown below:



[Workbooks](#)



[Interactive Lessons](#)



[Revision Questions](#)



[Help](#)

Clicking on either an icon or the hypertext link below the icon will take you to the corresponding web page containing links to the selected learning resources.

Workbooks:

There are fifty HELM Workbooks available to HEFCE-funded Higher Education Institutions in England and Northern Ireland from the Mathematics Education Centre at Loughborough University.

Access to these Workbooks is restricted to staff and students of these institutions and is controlled by each institution.

The List of Workbooks and Sections and some samples can be viewed on the HELM Website:

http://helm.lboro.ac.uk/pages/helm_workbooks.html

Interactive Lessons and Revision Questions:

HELM Interactive Lessons and Revision Questions are Authorware 7 applications. Prospective users need to have the appropriate Macromedia® Authorware® player (a web browser plug-in) installed in order to use these. The Authorware® player could be downloaded free of charge from:

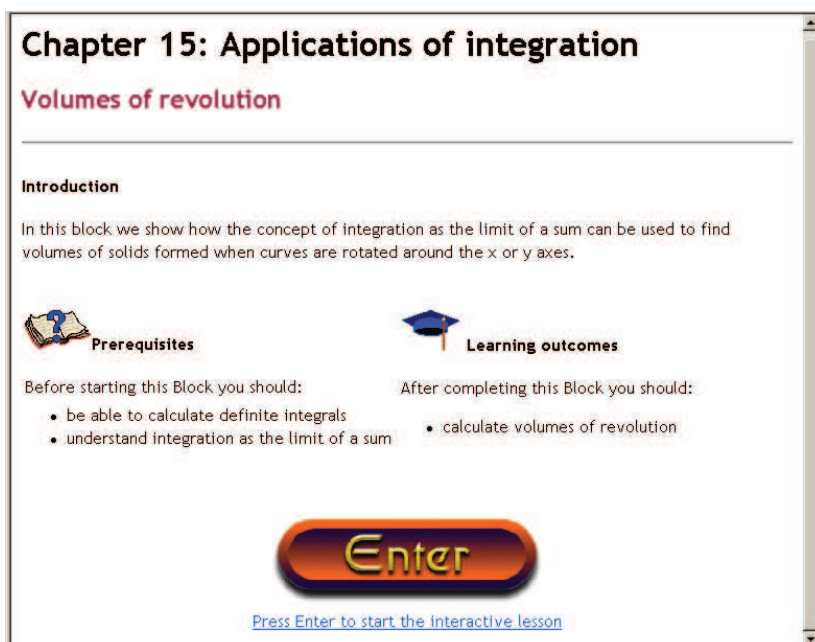
<http://www.adobe.com/shockwave/download/alternates/#ap> (as at June 2006)

It is important to **choose the correct version of the player** to support the browser and the computer platform being used. See the on-screen help file (by clicking HELP icon or the hyperlink) for further details.

Only selected sections of Workbooks 1-20 and 35-39 have associated Interactive Lessons and Revision Questions.

Caveat: Most of the Interactive Lessons and Revision Questions are derived from Loughborough's Open Learning Mathematics Project, which predated the HELM project, so the text may differ from that in the corresponding HELM Workbook.

Once you are in the page giving links to available lessons or questions, select the link you wish to continue with. An example for a lesson introduction page is given below.




Chapter 15: Applications of integration

Volumes of revolution


Introduction

In this block we show how the concept of integration as the limit of a sum can be used to find volumes of solids formed when curves are rotated around the x or y axes.

 **Prerequisites**

Before starting this Block you should:

- be able to calculate definite integrals
- understand integration as the limit of a sum

 **Learning outcomes**

After completing this Block you should:

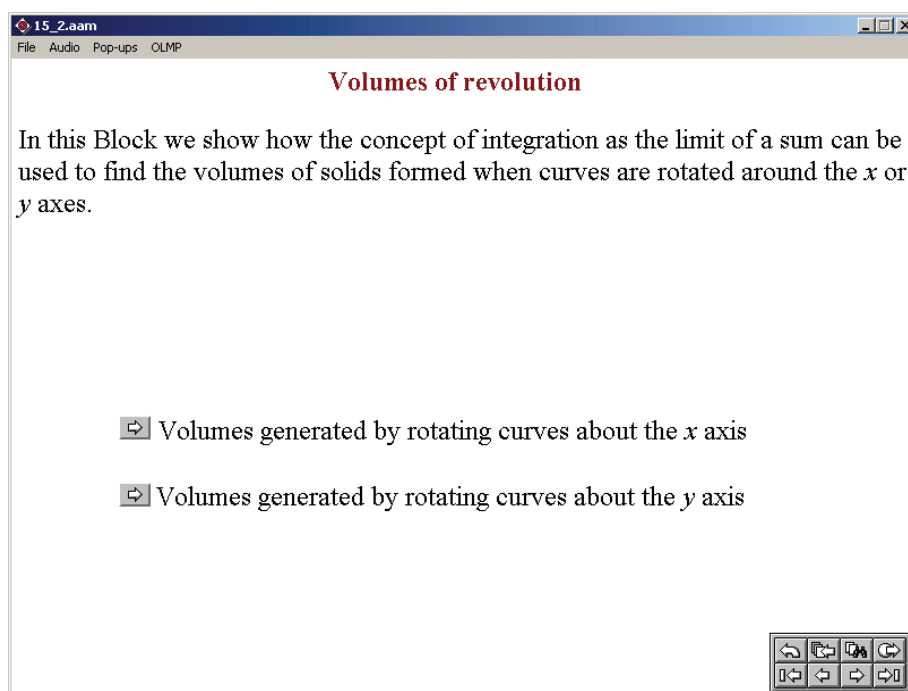
- calculate volumes of revolution

Enter

[Press Enter to start the interactive lesson](#)

The introduction page presents you with the title of the Workbook and the section that is covered by the resource you selected. It will also state the prerequisites and the learning outcomes.

Click on the button labelled “Enter” or on the hypertext link below the button to launch the Interactive Lesson or the Revision Questions. Provided that the correct web player plug-in is installed, the introduction page to the Interactive Lesson or the Revision Questions chosen will be displayed within the web browser. Patience may be needed as in some cases it may take a few seconds to load the application on to your web browser. The front page of the lesson will look similar to the following example.




Volumes of revolution


In this Block we show how the concept of integration as the limit of a sum can be used to find the volumes of solids formed when curves are rotated around the x or y axes.


Volumes generated by rotating curves about the x axis

Volumes generated by rotating curves about the y axis



As you see, there may be one or more buttons that will take you to a particular subsection of the lesson. For example, referring to the figure given below, clicking on the top button would take you to a section on Parametric differentiation; clicking the bottom button would take you to a section on Higher Derivatives.

 Parametric differentiation

 Higher derivatives

After you click on one of the buttons, the front page will disappear and you will see the first page of your chosen section. Look at the top right-hand corner of the screen: inside a box you will see in **green** something like "Page 1/2". This means that the section contains two pages of material and that you are on the first page. Note that a page can contain several screens of material.


The learning material is multimedia: a mix of text, graphics and sometimes sound. We think that the audio aspect of the material is useful, so you should use headphones if at all possible. The material is also interactive: most sections contain questions that you are expected to answer before proceeding. These questions might require you to use the mouse - to draw a vector, for instance. More often, they will require you to enter a number as the answer to a calculation. So be prepared: when you sit down at the computer make sure that you have with you a pen, some paper and a calculator.


Follow the instructions on the screen. Often, this means that you are presented with some text (maybe with some graphics) and then have to press the continue button in order to see more text. You will gain most from this activity if you think about the material. Try to anticipate what will come next; try to complete the next stage in an argument before it is presented to you; if you are asked to do something before proceeding - do it. Don't just sit there and idly press the continue button!


When a page is completed, the box at the top right-hand corner of the screen will turn **red**. You can then either navigate to the next page in the section, or return to the front page to choose another section. Or perhaps you want to quit the lesson altogether. These tasks are accomplished by using the navigation toolbar at the bottom right-hand corner of the screen and it is shown below. This toolbar is always visible. If you move your cursor over any icon in the toolbar, you will see a short pop-up message describing the icon's function. Once you have some experience with the system, this might prove irritating. You can turn off the pop-ups at any time by using the menu item entitled "Pop-ups", found at the top left-hand corner of your screen.





So that you have a permanent record, the icon functions are also described below.


To move to the next page of a section, click on: 


To move to the previous page of a section, click on: 


To return to the front page, click on: 

To quit the lesson at any time, click on: 

To move to the first page of a section, click on: 

To move to the last page of a section, click on: 

To get a list of previously viewed pages, click on:  and then select one from the list to visit that page.

To search for a word or a phrase, click on: 

In practice, the three navigation icons you will use most often are:

1. The icon that takes you to the next page
2. The icon that returns you to the title page
3. The icon that lets you quit.

Feel free to view each page of the Interactive Lessons as many times as you like. Note that many of the pages have random variables embedded within them, so that each time you view the page you see slightly different examples.

Similarly, you may attempt the Revision Questions as often as you wish. Nearly all of the Revision Questions are generated using random numbers so that you seldom get the same question twice. These questions are presented within the context of the theoretical material that is applicable to a particular Workbook. Once you have worked through a Workbook, though, you might want to gain more practice at doing questions without having to wade through the relevant background theory.

General Advice to Students Studying Mathematics

49.4

1. Communication with the lecturer or tutor

When your lecturer or tutor writes something that you cannot understand, says something which you don't hear clearly, or provides notes which seem unintelligible or wrong, don't be reluctant to query it! Almost certainly you won't be the only one with this problem. Help yourself and the rest of the class. You will also be doing the lecturer or tutor a favour. Furthermore, ask the question as soon as you reasonably can. Waiting until the end of class can be very frustrating for all concerned!

2. Reading instructions

It seems human nature not to want to read instructions properly (if at all) when faced with a practical task. This even applies to mathematics problem sheets, to coursework and to examination papers. Careful reading of instructions is especially important in mathematics, otherwise you can finish up giving the right answer to the wrong problem and so gaining little or no credit when credit is really due. Miscopying the question is easily done in mathematics and can have dire consequences. It is easy to turn a simple problem into a fiendishly difficult one by doing that - and not only losing credit for that question but also wasting a lot of time (which may well indirectly lead to further loss of credit).

3. Handwriting

If your handwriting is not clear your tutor will have difficulty reading your work when trying to help you, and when marking your work may misread what you intended or get frustrated and lose patience and so not award the mark that the work merits. It has even been known for students to find it hard to read their own writing a few days later!

What are your particular idiosyncrasies in handwriting, which lead to misreading? Be aware and avoid them when it really matters!

Here are some possibilities for confusion (but there many others!)

- + and t
- 0 and o and O (zero and lower and upper case letter 'oh')
- 1 and l and / and l and i ('one' ; letter 'ell' ; 'slash' or 'solidus'; letters "l" and "i")
- 2 and z
- j and y and g
- \times and x (times sign and letter 'x')

Clarifying what you mean by use of brackets is discussed later, but here is an example where you either must write very clearly or resort to brackets to avoid ambiguity:

What do you mean by $\sqrt{3}/2$? Is it $(\sqrt{3})/2$ or $\sqrt{(3/2)}$? You can express whichever you mean more clearly by writing it as either $\frac{\sqrt{3}}{2}$ or $\sqrt{\frac{3}{2}}$, or by using brackets.

4. Calculators

Although calculators are much better at doing calculations than students they do not always give the right answer.

One of the commonest error with calculators is **forgetting to switch between degrees and radians**. Radians are invariably used in calculus and it is sensible to keep your calculator in this mode. (It is only if x is in radians that the derivative of $\sin(x)$ is $\cos(x)$, for example.)

Another error arises when using graphics facilities. Some graphic calculators only display the right half of the graph $y = x^{1/2}$ if the general root key ($\sqrt[x]{y}$) is used but will give both halves if there is a special cube root button ($\sqrt[3]{}$) which is used.

(The explanation lies in the fact that the general root key ($\sqrt[x]{y}$) uses logarithms during the computational process and, since the log of a negative number is not defined, the negative part is "lost".)

5. Brackets (aka parentheses)

Omitting pairs of brackets can lead to faulty algebraic manipulations and incorrect numerical computations.

Expanding $-2 \times (p - q)$ should lead to $-2p + 2q$ but if (through laziness) it is expressed as $-2 \times p - q$ then the outcome is likely to be $-2p - q$ or maybe $-2p - 2q$.

Expressing $-3(x+1)^2$ as $-3 \times x^2 + 2x + 1$ is a recipe for disaster leading to $-3x^2 + 2x + 1$ instead of $-3x^2 - 6x - 3$.

(Incidentally, a more subtle error is the belief that a **minus sign means a negative number**. This is not true if x is a negative number, of course.)

Writing fractions can be a problem. For instance, if you write “ $2/7y$ ” do you mean “ $(2/7)y$ ” or “ $2/(7y)$ ”? To be safe you can insert brackets in such an expression or write it clearly as either $\frac{2}{7}y$ or $\frac{2}{7y}$ as appropriate.

In integration, too, problems can easily arise:

$$2 \int (4x^3 + 4x - 3) dx = 2 \times x^4 + 2x^2 - 3x + \text{constant} = 2x^4 + 2x^2 - 3x + C \quad \text{WRONG!}$$

It should be

$$2 \int (4x^3 + 4x - 3) dx = 2(x^4 + 2x^2 - 3x) + C = 2x^4 + 4x^2 - 6x + C \quad \text{RIGHT!}$$

In general, **if in any doubt put in brackets**. This nearly always works.

6. BODMAS to the rescue!

Order of operations

Common mathematical practice is to perform particular mathematical operations in certain orders. Such conventions reduce the number of brackets needed. For example, it is understood that “ $4x+3$ ” means “ $(4x+3)$ ”, and never “ $4(x+3)$ ”. In general multiplication is performed **before** (has precedence over) addition. This priority can be reversed by inserting brackets if necessary. It is essential to use the correct order (precedence) of these operations in arithmetic and algebra.

What is -4^2 ? It is tempting to think that the expression means $(-4)^2$ which is $+16$ but the mathematical convention is to perform the exponentiation operation before applying the negation operation (represented by the minus sign), and so -4^2 is actually $-(4^2)$, which is -16 .

These conventions are encapsulated in the BODMAS rule for deciding the order in which to do mathematical operations. (This is introduced in HELM Workbook 1.)

BODMAS: (Brackets, 'Of', Division, Multiplication, Addition, Subtraction):

1. **B**rackets take highest priority - deal with items inside a pair of brackets first.
2. **O**f is a form of multiplication (e.g. 'half of 10' means $1/2 \times 10$) and comes next.
3. **D**ivision and **M**ultiplication come next and left-to-right order is required (e.g. $4 \div 7x \times k$ is evaluated as $(4 \div 7) \times k$ and not as $4 \div (7x \times k)$).
4. **A**ddition and **S**ubtraction come last (in either order will do but left-to-right is normal).

When faced with several operations at the same level of precedence the left-to-right order is normally used, but it is not essential.

Beware of calculators

Not all calculators follow these conventions in all circumstances, and ambiguities can arise, so you should check what you get for operations such as $4 \div 7 \times 7$, $2 - 3^2$ and 3^{2+1} . Inserting brackets will sort out these problems if you are unsure what your calculator will do, or if you want to force it to do something it won't do otherwise.

7. Equality and Identity

The equals sign (=) is often wrongly used as a shorthand symbol for "gives" or "leads to" or like phrases. For instance, when finding the third derivative of $x^3 + 2x - 3$, some students will write

$$\frac{d^3}{dx^3}(x^3 + 2x - 3) = 3x^2 + 2 = 6x = 6$$

These four expressions are not equal of course.

This practice is more annoying to the tutor than harmful to the student!

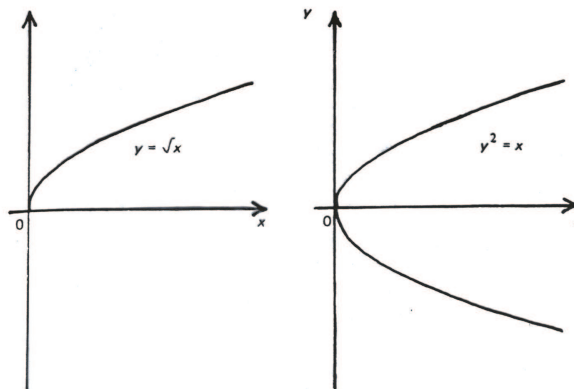
The use of = is commonplace throughout mathematics and hides the distinction between expressions which are true for particular values (e.g. $2x = 2$) and those, which are ALWAYS true (e.g. $2x = x + x$). The special identity symbol (\equiv) is (or rather can be) used for these: e.g. $2x \equiv x + x$. This symbol has been used sometimes in the HELM Workbooks where emphasis is important (especially in Workbook 1: Basic Algebra and in Workbook 4: Trigonometry) but we *have not done so consistently* - it just isn't the way mathematicians and engineers work! In practice it is nearly always obvious from the context, which is meant.

8. Notational problems

Square root symbol

Every positive number has two real square roots. The expression \sqrt{n} actually means “the **non-negative** square root of n ,” but many think it can represent either of the square roots of n - i.e., it represents two numbers. This error is actually encouraged by the common practice of referring to \sqrt{n} as “**the** square root of ” instead of the more carefully worded “the **positive** square root of ”. In fact even that phrase isn’t quite correct in all circumstances since it could be zero!

The graphs of $y = \sqrt{x}$ and $y^2 = x$ below illustrate the point:



If you want to refer to both roots then you must use $\pm\sqrt{\quad}$, as in the quadratic formula:

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

What about $x^{\frac{1}{2}}$? Usually this is taken to mean \sqrt{x} but, particularly in complex number work, it can mean **any** value of the root. So $y = x^{\frac{1}{2}}$ could mean either of the graphs shown above!

Another common error is to replace $\sqrt{1 - \sin^2 \theta}$ by $\cos \theta$ (because $1 - \sin^2 \theta \equiv \cos^2 \theta$). This is wrong because $\cos \theta$ can be negative whereas $\sqrt{\quad}$ is never negative, so the result should be expressed as $|\cos \theta|$.

Trigonometric inverses

The expression $\sin^k x$ is interpreted in different ways, depending on the value of k .

$$\sin^3 x \equiv (\sin x)^3 \quad \text{and similarly for cos, tan, sec, cosec and cot}$$

but

$\sin^{-1} x$ means the inverse sine function, sometimes written as $\arcsin(x)$, and similarly for cos, tan, sec, cosec and cot.

Note that $\arcsin(x) \neq (\sin x)^{-1}$ but $\operatorname{cosec}(x) \equiv (\sin x)^{-1}$ because ...

\sin^{-1} is the **inverse function** to \sin

$1/\sin$ is the **reciprocal function** of \sin , which is called cosec .

9. Checking your work

Human nature seems to lead to most of us being overconfident in our ability to be accurate. In day-to-day life (and indeed in engineering) some imprecision is often acceptable (such as when driving a car, unless in a Formula One race perhaps). But this is not so in mathematics where **absolute** accuracy is demanded. It is vitally important to check your work. (Of course in a timed examination the benefit and disadvantage of checking have to be weighed against each other and will depend upon the circumstances and personal traits.) Ideally you should check by using some alternative method but whether you use the same method or a different one is less important than the act of checking itself.

When solving an algebraic equation (or differential equation), normally an easy way to check the answer is to substitute the result back into original equation, and see if it satisfies the equation. This leads us onto the next more specific situation where checking is very important.

10. Irreversible steps in solving equations

If you apply the same operations to both sides of an equation, the result must be another equation (i.e. the equality must be preserved). The new equation must have all the solutions that the original equation has. **BUT it might also have some new solutions.** This may not seem logical or even possible but unfortunately it is the case when you apply certain operations (which are not reversible).

Reversible operations

1. Multiplying both sides of an equation (except by zero) is reversible: e.g. “multiply both sides by 3”: the set of values of x which satisfy $2x^2 = 11x - 5$ is exactly the same as the set of values of x that satisfy $6x^2 = 33x - 15$ [i.e. $x = 5$ and $x = \frac{1}{2}$]. (We can simply reverse the operation here by multiplying both sides by $\frac{1}{3}$.)
2. Cubing both sides of an equation is reversible: e.g. the set of values of x which satisfy $x + 1 = -3$ is exactly the same as the set of values of x that satisfy $(x + 1)^3 = -27$ [i.e. $x = -3$ only]. (We can simply reverse the operation here by cube rooting both sides.)
3. Subtraction is reversible: e.g. “subtract 8 from both sides”. The set of values of x which satisfy $2x^2 = 8$ is exactly the same as the set of values of x that satisfy $2x^2 - 8 = 0$. [i.e. $x = 2$ and $x = -2$] (We can simply reverse the operation here by adding 8 to both sides.)

Irreversible operations

Some operations are not reversible, and using them can introduce new solutions (called extraneous solutions) not valid for the original equation.

1. Square rooting is irreversible: e.g. $x = -9$ has only one solution, which is $x = -9$ of course, but after squaring both sides we get $x^2 = 81$, which has two solutions, $x = 9$ and $x = -9$.
2. Multiplication of an equation in variable x by x is irreversible: this always introduces a solution $x = 0$: e.g. $2x^2 = 8$ has two roots 2 and -2 but $2x^3 = 8x$ has three roots 2 and -2 and 0.
3. More generally, multiplication of an equation in variable x by $x - c$ is irreversible: the resulting equation will have the additional new solution $x = c$. [The reason is that multiplying any equation by zero preserves the equality and the factor $x - c$ is zero when $x = c$.]

When any steps taken involve an irreversible operation, then it is essential to check for extraneous roots at the end.

The most common irreversible operation used in solving equations is squaring.

11. Additivity of operations

Many students confuse operations which are additive and those which are not. The normal (wrong) assumption is that the operation will be additive.

An operation f is **additive** if it satisfies $f(x+y) = f(x)+f(y)$ for all x and y . E.g. $2(x+y) = 2x+2y$.

This is **true for some operations**. Examples are:

1. Algebra: $k(p + q) = kp + kq$
2. Differentiation: $d(u + v)/dx = du/dx + dv/dx$
3. Integration: $\int (u + v)dx = \int u dx + \int vdx$
4. Laplace transformation: $\mathcal{L}(f + g) = \mathcal{L}(f) + \mathcal{L}(g)$
5. Matrix (transposition): $(A + B)^T = A^T + B^T$

It is **not true for most** operations. Examples are:

1. Trigonometric identities: e.g. $\sin(x + y) \neq \sin(x) + \sin(y)$
2. Raising to a power: e.g. $(x + y)^2 \neq x^2 + y^2$

3. Taking square root: e.g. $\sqrt{x^2 + y^2} \neq \sqrt{x^2} + \sqrt{y^2}$
4. Exponentiation: $\exp(x + y) \neq \exp(x) + \exp(y)$
5. Taking logarithm: $\log(x + y) \neq \log(x) + \log(y)$
6. Matrices (inversion): $(A + B)^{-1} \neq A^{-1} + B^{-1}$

This is a common mistake made by first year undergraduates who have not studied mathematics for some time.

12. Commutativity of operations

Two operations f and g **commute** if you get the same result when you perform them in either order: i.e. $f(g(x)) = g(f(x))$. E.g. if f means “doubling” and g means “trebling” then $f(g(5)) = f(15) = 30$ and $g(f(5)) = g(10) = 30$ so $f(g(5)) = g(f(5))$.

This is **true for some** combinations of operations. Examples are:

1. Powers and roots of positive numbers: $(\sqrt{x})^3 = \sqrt{(x^3)}$
2. Multiplication by a constant and integration: $2 \int u \, dx = \int 2u \, dx$

It is **not true for most** combinations of operations. Examples are:

1. “Doubling” and “Adding 1” \neq “Adding 1” and “Doubling”
2. Powers and addition: $(x + 1)^3 \neq x^3 + 1^3$
3. Taking cosine and squaring: $\cos(x^2) \neq \{\cos(x)\}^2$
4. Multiplication and differentiation: $(u \times v)' \neq u' \times v'$
5. Division and integration: $\int (u/v) \, dx \neq \int u \, dx / \int v \, dx$

13. Dimensions and scaling

Dimensional analysis is an important topic for engineers and is treated in Workbook 47. It doesn't tell you if you have the right formula or answer, but it can indicate that something must be wrong. Here are some simple examples:

1. If you're asked to find a length, and your answer is some number of square cms, then you must have made an error somewhere.

- If you're asked to find an area and your answer is a negative number, then you know you've made an error somewhere UNLESS it is a calculus problem (where an area below the axis may be represented as a negative quantity).
- The formula for the area, S , of a triangle with sides a, b, c must have dimensions of area so it cannot possibly be either of the following:

$$S = a \times b \times c \quad \text{or} \quad S = a + b + c$$

It might in theory be

$$S = (a + b + c)^2$$

which has the right dimensions for area, though that isn't actually correct of course!

There is in fact a complicated formula involving only a, b, c for S , called Heron's formula:

$$S = \sqrt{\{(a + b + c)(b + c - a)(c + a - b)(a + b - c)/16\}}.$$

You can check that this is dimensionally correct.

Unit Conversion

A related problem is converting from one unit to another. Just because $1 \text{ m} = 100 \text{ cm}$ does not mean that $1 \text{ m}^3 = 100 \text{ cm}^3$. Obvious, perhaps, but an easy mistake to make when not concentrating. In fact, of course, there are three dimensions here so the scale factor is 100^3 and $1 \text{ m}^3 = 1\,000\,000 \text{ cm}^3$.

Scaling error

If the question is a real-world problem, you should ask: "Is my answer sensible?" For instance, if you are given a list of the main components used in the manufacture of a truck and are asked to estimate its unladen weight, and you come up with an answer of 1000 tonnes, then you must have made a mistake either in the calculations or in the units.

14. Some further traps

It is important to remember the following:

(a) Cancelling in fractions

Don't fall into the trap of *partial cancelling*.

This is correct:

$$\frac{(x-1)\cancel{(x+2)}}{(x+3)\cancel{(x+2)}} = \frac{(x-1)}{(x+3)} \quad (\text{provided } x \neq -2)$$

but this is NOT correct:

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

You only cancel once when the factors in the numerator are multiplied but you must cancel each time when the factors in the numerator are added (or subtracted).

(b) Inequalities

$x \leq 2$ and $x \geq -1$ can be combined to give $-1 \leq x \leq 2$

BUT $x \geq 2$ and $x \leq -1$ cannot be combined to give $2 \geq x \leq -1$, which makes no sense. It is not possible to express these as a single equality (because it would imply $2 \leq -1$!).

(c) Solving equations

$$(x-1)(x-2) = 0 \Rightarrow x-1 = 0 \text{ or } x-2 = 0 \quad \text{TRUE!}$$

BUT

$$(x-1)(x-2) = 2 \Rightarrow x-1 = 2 \text{ or } x-2 = 2 \quad \text{FALSE!}$$

It is only with zero right-hand side that such factorisation is valid.

(d) Differentiation

The term $\frac{dy}{dx}$ indicates differentiation of the expression y with respect to the variable x . The operation of differentiation itself can be expressed as $\frac{d}{dx}$. It is not strictly correct to separate out the dy and the dx as in $\frac{dy}{dx} = x^2 \Rightarrow dy = x^2 dx$ but this does work (in solving differential equations), however mathematicians don't like it!

(e) Integration

$$\int \frac{1}{x} dx = \ln(x) + c \quad \text{NOT CORRECT!}$$

$$\int \frac{1}{x} dx = \ln|x| + c \quad \text{CORRECT!}$$

15. Stationary Points and Points of Inflection

Most students (and some teachers!) have an imperfect understanding of the definitions of local maximum, local minimum and point of inflection. Simple graphs can be used to illustrate these features.

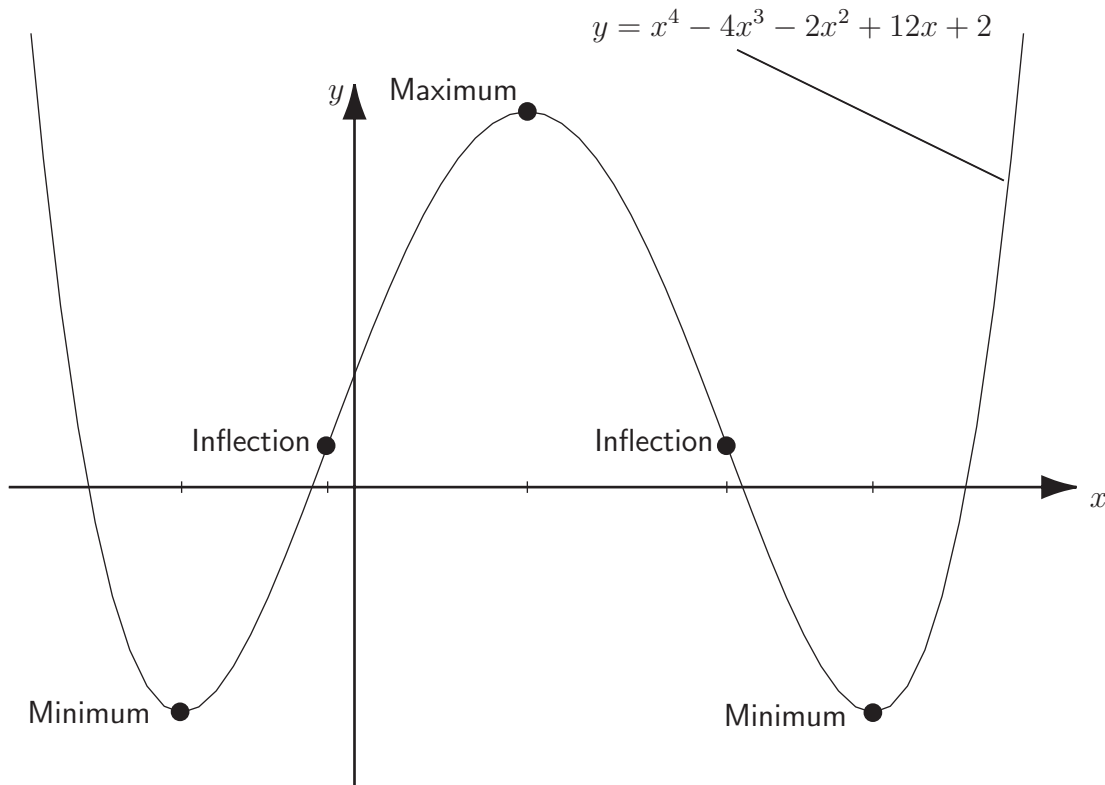
Of the following three statements only the first two are known with any certainty by most students:

Given a twice differentiable function f for which $f'(a) = 0$

- (1) If $f''(a) > 0$, then $f(x)$ has a minimum when $x = a$,
- (2) If $f''(a) < 0$, then $f(x)$ has a maximum when $x = a$,
- (3) If $f''(a) = 0$, then $f(x)$ has minimum or a maximum or a point of inflection when $x = a$.

Many students think (3) **always** leads to a point of inflection but the graph of $f(x) = x^4$ clearly shows this to be untrue when $x = 0$.

Another misconception is that a point of inflection **requires** $f'(a) = 0$. This is not true as can easily be seen, for example, on the sine curve. This raises another point - for any continuous function there is always a point of inflection between every local minimum and local maximum. The graph below highlights these features.



Maxima and Minima without Calculus

Students all too readily turn to the calculus when needing to find maxima and minima. There are, however, cases when alternative approaches are simpler, quicker or more informative:

Example 1

Find the minimum value of $f(x) \equiv x^2 + 2x + 3$.

Completing the square gives $f(x) = (x + 1)^2 + 2$.

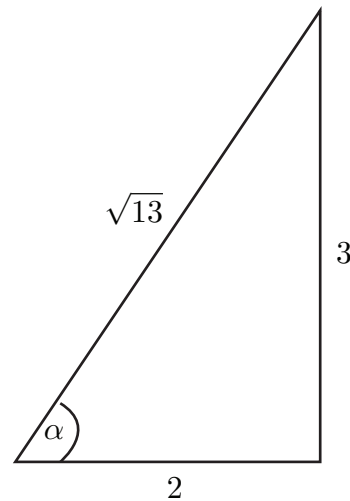
This clearly is a minimum when $x = -1$ and there $f(x)$ has value 2.

Example 2

Find the maximum value of $f(x) \equiv 2 \sin(x) + 3 \cos(x)$.

Using the trigonometric identity $\sin(A + B) \equiv \sin A \cos B + \cos A \sin B$ and utilising the triangle in the diagram we have

$$\begin{aligned} f(x) &= \sqrt{13} \left[\frac{2}{\sqrt{13}} \sin x + \frac{3}{\sqrt{13}} \cos x \right] \\ &= \sqrt{13} [\cos \alpha \sin x + \sin \alpha \cos x] \\ &= \sqrt{13} \sin(x + \alpha) \end{aligned}$$



This clearly has a maximum value of $\sqrt{13}$ at $x = \frac{\pi}{2} - \alpha$ (for example), which is where $\sin(x + \alpha) = \sin\left(\frac{\pi}{2}\right) = 1$.

Some Useful Websites 49.5

- (a) The reader is referred to the excellent website
<http://atlas.math.vanderbilt.edu/~schecktex/commerrs/>
in which useful discussion of many intriguing errors and pitfalls are found and tips on avoiding them.
In particular, errors in calculus including integration by parts and solving differential equations are discussed at some length.
- (b) See also the *Maths Mistakes* website (a site dedicated to the listing of mathematical mistakes made by advertisers, the media, reporters, politicians, activists and others) where you can marvel at the mistakes which others (not students) make:
<http://members.cox.net/mathmistakes/>
- (c) Another valuable site is Eric Weisstein's Mathworld supported by Wolfram Research:
<http://mathworld.wolfram.com/>
which has a wealth of material, where you can look up definitions and formulae etc.
- (d) Finally, the Wikipedia free encyclopaedia has a section on Mathematics where you can look up almost anything, useful or otherwise:
<http://en.wikipedia.org/wiki/Category:Mathematics>

There are, of course, hundreds of other websites to explore . . .

List of Sections in Workbooks 1 - 48

49.6

Workbook 1 - Basic Algebra (89 pages)	
1.1	Mathematical Notation and Symbols
1.2	Indices
1.3	Simplification and Factorisation
1.4	Arithmetic of Algebraic Fractions
1.5	Formulae and Transposition
Workbook 2 - Basic Functions (75 pages)	
2.1	Basic Concepts of Functions
2.2	Graphs of Functions and Parametric Form
2.3	One-to-one and Inverse Functions
2.4	Characterising Functions
2.5	The Straight Line
2.6	The Circle
2.7	Some Common Functions
Workbook 3 - Equations, Inequalities and Partial Fractions (71 pages)	
3.1	Solving Linear Equations
3.2	Solving Quadratic Equations
3.3	Solving Polynomial Equations
3.4	Solving Simultaneous Linear Equations
3.5	Solving Inequalities
3.6	Partial Fractions
Workbook 4 - Trigonometry (77 pages)	
4.1	Right-angled Triangles
4.2	Trigonometric Functions
4.3	Trigonometric Identities
4.4	Applications of Trigonometry to Triangles
4.5	Applications of Trigonometry to Waves
Workbook 5 - Functions and Modelling (49 pages)	
5.1	The Modelling Cycle and Functions
5.2	Quadratic Functions and Modelling
5.3	Oscillating Functions and Modelling
5.4	Inverse Square Law Modelling

Workbook 6 - Exponential and Logarithmic Functions (73 pages)	
6.1	The Exponential Function
6.2	The Hyperbolic Functions
6.3	Logarithms
6.4	The Logarithmic Function
6.5	Modelling Exercises
6.6	Log-linear Graphs
Workbook 7 - Matrices (50 pages)	
7.1	Introduction to Matrices
7.2	Matrix Multiplication
7.3	Determinants
7.4	The Inverse of a Matrix
Workbook 8 - Matrix Solution of Equations (32 pages)	
8.1	Solution by Cramer's Rule
8.2	Solution by Inverse Matrix Method
8.3	Solution by Gauss Elimination
Workbook 9 - Vectors (66 pages)	
9.1	Basic Concepts of Vectors
9.2	Cartesian Components of Vectors
9.3	The Scalar Product
9.4	The Vector Product
9.5	Lines and Planes
Workbook 10 - Complex Numbers (34 pages)	
10.1	Complex Arithmetic
10.2	Argand Diagrams and the Polar Form
10.3	The Exponential Form of a Complex Number
10.4	De Moivre's Theorem
Workbook 11 - Differentiation (58 pages)	
11.1	Introducing Differentiation
11.2	Using a Table of Derivatives
11.3	Higher Derivatives
11.4	Differentiating Products and Quotients
11.5	The Chain Rule
11.6	Parametric Differentiation
11.7	Implicit Differentiation

Workbook 12 - Applications of Differentiation (63 pages)	
12.1	Tangents and Normals
12.2	Maxima and Minima
12.3	The Newton-Raphson Method
12.4	Curvature
12.5	Differentiation of Vectors
12.6	Case Study: Complex Impedance
Workbook 13 - Integration (62 pages)	
13.1	Basic Concepts of Integration
13.2	Definite Integrals
13.3	The Area Bounded by a Curve
13.4	Integration by Parts
13.5	Integration by Substitution and Using Partial Fractions
13.6	Integration of Trigonometric Functions
Workbook 14 - Applications of Integration 1 (34 pages)	
14.1	Integration as the Limit of a Sum
14.2	The Mean Value and the Root-Mean-Square Value
14.3	Volumes of Revolution
14.4	Lengths of Curves and Surfaces of Revolution
Workbook 15 - Applications of Integration 2 (31 pages)	
15.1	Integration of Vectors
15.2	Calculating Centres of Mass
15.3	Moment of Inertia
Workbook 16 - Sequences and Series (51 pages)	
16.1	Sequences and Series
16.2	Infinite Series
16.3	The Binomial Series
16.4	Power Series
16.5	Maclaurin and Taylor Series
Workbook 17 - Conics and Polar Coordinates (43 pages)	
17.1	Conic Sections
17.2	Polar Coordinates
17.3	Parametric Curves
Workbook 18 - Functions of Several Variables (40 pages)	
18.1	Functions of Several Variables
18.2	Partial Derivatives
18.3	Stationary Points
18.4	Errors and Percentage Change

Workbook 19 - Differential Equations (70 pages)	
19.1	Modelling with Differential Equations
19.2	First Order Differential Equations
19.3	Second Order Differential Equations
19.4	Applications of Differential Equations
Workbook 20 - Laplace Transforms (73 pages)	
20.1	Causal Functions
20.2	The Transform and its Inverse
20.3	Further Laplace Transforms
20.4	Solving Differential Equations
20.5	The Convolution Theorem
20.6	Transfer Functions
Workbook 21 z -Transforms (96 pages)	
21.1	z -Transforms
21.2	Basics of z -Transform Theory
21.3	z -Transforms and Difference Equations
21.4	Engineering Applications of z -Transforms
21.5	Sampled Functions
Workbook 22 - Eigenvalues and Eigenvectors (53 pages)	
22.1	Basic Concepts
22.2	Applications of Eigenvalues and Eigenvectors
22.3	Repeated Eigenvalues and Symmetric Matrices
22.4	Numerical Determination of Eigenvalues and Eigenvectors
Workbook 23 - Fourier Series (73 pages)	
23.1	Periodic Functions
23.2	Representing Periodic Functions by Fourier Series
23.3	Even and Odd Functions
23.4	Convergence
23.5	Half-range Series
23.6	The Complex Form
23.7	An Application of Fourier Series
Workbook 24 - Fourier Transforms (37 pages)	
24.1	The Fourier Transform
24.2	Properties of the Fourier Transform
24.3	Some Special Fourier Transform Pairs

Workbook 25 - Partial Differential Equations (42 pages)	
25.1	Partial Differential Equations
25.2	Applications of PDEs
25.3	Solution using Separation of Variables
25.4	Solutions using Fourier Series
Workbook 26 - Functions of a Complex Variable (58 pages)	
26.1	Complex Functions
26.2	Cauchy-Riemann Equations and Conformal Mappings
26.3	Standard Complex Functions
26.4	Basic Complex Integration
26.5	Cauchy's Theorem
26.6	Singularities and Residues
Workbook 27 - Multiple Integration (83 pages)	
27.1	Introduction to Surface Integrals
27.2	Multiple Integrals over Non-rectangular Regions
27.3	Volume Integrals
27.4	Changing Coordinates
Workbook 28 - Differential Vector Calculus (53 pages)	
28.1	Background to Vector Calculus
28.2	Differential Vector Calculus
28.3	Orthogonal Curvilinear Coordinates
Workbook 29 - Integral Vector Calculus (77 pages)	
29.1	Line Integrals Involving Vectors
29.2	Surface and Volume Integrals
29.3	Integral Vector Theorems
Workbook 30 - Introduction to Numerical Methods (64 pages)	
30.1	Rounding Error and Conditioning
30.2	Gaussian Elimination
30.3	LU Decomposition
30.4	Matrix Norms
30.5	Iterative Methods for Systems of Equations
Workbook 31 - Numerical Methods of Approximation (86 pages)	
31.1	Polynomial Approximations
31.2	Numerical Integration
31.3	Numerical Differentiation
31.4	Nonlinear Equations

Workbook 32 - Numerical Initial Value Problems (80 pages)	
32.1	Initial Value Problems
32.2	Linear Multistep Methods
32.3	Predictor-Corrector Methods
32.4	Parabolic PDEs
32.5	Hyperbolic PDEs
Workbook 33 - Numerical Boundary Value Problems (36 pages)	
33.1	Two-point Boundary Value Problems
33.2	Elliptic PDEs
Workbook 34 - Modelling Motion (63 pages)	
34.1	Projectiles
34.2	Forces in More Than One Dimension
34.3	Resisted Motion
Workbook 35 - Sets and Probability (53 pages)	
35.1	Sets
35.2	Elementary Probability
35.3	Addition and Multiplication Laws of Probability
35.4	Total Probability and Bayes' Theorem
Workbook 36 - Descriptive Statistics (45 pages)	
36.1	Describing Data
36.2	Exploring Data
Workbook 37 - Discrete Probability Distributions (60 pages)	
37.1	Discrete Probability Distributions
37.2	The Binomial Distribution
37.3	The Poisson Distribution
37.4	The Hypergeometric Distribution
Workbook 38 - Continuous Probability Distributions (27 pages)	
38.1	Continuous Probability Distributions
38.2	The Uniform Distribution
38.3	The Exponential Distribution
Workbook 39 - The Normal Distribution (39 pages)	
39.1	The Normal Distribution
39.2	The Normal Approximation to the Binomial Distribution
39.3	Sums and Differences of Random Variables

Workbook 40 - Sampling Distributions and Estimation (22 pages)	
40.1	Sampling Distributions
40.2	Interval Estimation for the Variance
Workbook 41 - Hypothesis Testing (42 pages)	
41.1	Statistics Testing
41.2	Tests Concerning a Single Sample
41.3	Tests Concerning Two Samples
Workbook 42 - Goodness of Fit and Contingency Tables (24 pages)	
42.1	Goodness of Fit
42.2	Contingency Tables
Workbook 43 - Regression and Correlation (32 pages)	
43.1	Regression
43.2	Correlation
Workbook 44 - Analysis of Variance (57 pages)	
44.1	One-Way Analysis of Variance
44.2	Two-Way Analysis of Variance
44.3	Experimental Design
Workbook 45 - Non-parametric Statistics (36 pages)	
45.1	Non-parametric Tests for a Single Sample
45.2	Non-parametric Tests for Two Samples
Workbook 46 - Reliability and Quality Control (38 pages)	
46.1	Reliability
46.2	Quality Control
Workbook 47 - Mathematics and Physics Miscellany (69 pages)	
47.1	Dimensional Analysis in Engineering
47.2	Mathematical Explorations
47.3	Physics Case Studies
Workbook 48 - Engineering Case Studies (97 pages)	
	Engineering Case Studies 1 to 20

Index of Engineering Contexts in Workbooks 1 to 48

49.7

Engineering Topic	Workbook	Page Number
Acceleration in polar coordinates	Wbk 47	67
Admittance of an electronic circuit	Wbk 3	69
Aerofoil	Wbk 26	14, 19
Aircraft	Wbk 9	13
Aircraft wings	Wbk 42	4
Aircraft wings	Wbk 45	26
Airline booking	Wbk 39	29
Alloy impurities	Wbk 41	18
Alloy spacers	Wbk 44	4, 16
Alloy stretching	Wbk 45	27
Alloy-twisting resistance	Wbk 45	26
Aluminium alloy tensile strength	Wbk 44	45
Aluminium sheet faults	Wbk 42	4
Amplifier	Wbk 10	26
Amplitude	Wbk 3	67, 74
Amplitude modulation	Wbk 4	47
Amusement rides	Wbk 34	6, 43-50
An LC circuit with sinusoidal input	Wbk 19	48
An RC circuit with single frequency input	Wbk 19	26
Angular velocity of Earth	Wbk 34	40
Anti-lock brakes	Wbk 45	11
Arrhenius' law	Wbk 6	32
Assembly machines	Wbk 44	33
Asteroid	Wbk 17	22
Atomic theory	Wbk 47	13, 14
Ball bearing diameters	Wbk 40	19
Banked tracks	Wbk 34	49
Basketball	Wbk 34	26
Battery lifetime	Wbk 41	15
Beam	Wbk 19	65, 67
Beam	Wbk 20	52
Beam deflection	Wbk 48	20
Beam deformation	Wbk 48	15
Beats	Wbk 19	64
Bending moment for a multiple structure	Wbk 48	35
Bending moment of beam	Wbk 19	65

Bending moment of beam	Wbk 43	18
Bicycle	Wbk 34	41
Black body radiation	Wbk 47	38, 41, 43, 46
Bolt hole diameters	Wbk 40	20
Bottle design	Wbk 31	52-54
Brake	Wbk 4	14
Buckling of a strut	Wkb 12	44
Buckling of columns	Wbk 48	26
Buffer	Wbk 20	39
Cable	Wbk 15	21
Cable	Wbk 43	7, 12
Cable breaking strength	Wbk 45	31
Cable suspended	Wbk 48	40
Calculator battery life	Wbk 41	15
Capacitor	Wbk 20	49
Car accessories	Wbk 35	18
Cartons for powder	Wbk 41	13
Castings	Wbk 41	9
Catalysts	Wbk 44	49
CD player output	Wbk 42	7
Centre of mass	Wbk 27	55-65
Centre of pressure	Wbk 27	15
Chain alloy	Wbk 45	27
Charge	Wbk 9	40
Charge on a capacitor	Wbk 20	49
Chemical process	Wbk 44	49
Chemical reaction	Wbk 6	32
Circle cutting machine	Wbk 17	10
Circular motion	Wbk 34	35
Coconut shy	Wbk 34	25
Columns buckling	Wbk 48	26
Communication network	Wbk 1	52
Communication network	Wbk 7	27
Component lifetime	Wbk 38	24, 25
Component variation	Wbk 39	17, 18-20
Compressive strength of blocks	Wbk 45	4, 14
Compressive strength of concrete	Wbk 44	43
Concrete compressive strength	Wbk 44	43
Conductor coating	Wbk 38	21
Conservation of energy	Wbk 34	28
Control charts	Wbk 46	24-38
Cornering of vehicle	Wbk 34	36-39, 51
Crank mechanism	Wbk 4	62
Crank used to drive a piston	Wbk 12	33
Current	Wbk 11	21
Current associated with magnetic field	Wbk 28	28
Current in line	Wbk 29	26, 67

Current in loop	Wbk 29	27
Currents in a ladder network	Wbk 21	60
Currents in three loops	Wbk 8	30
Currents in two loops	Wbk 8	16
Cutting steel quality	Wbk 45	9
Dam	Wbk 27	3, 15, 36
Defective components	Wbk 35	48
Defects (in components and products)	Wbk 37	8, 19, 20, 23, 24, 40, 42, 54-58
Deflection of a beam	Wbk 48	20
Deflection of a uniformly loaded beam	Wbk 19	67
Deflection of a uniformly loaded beam	Wbk 20	52
Demodulation	Wbk 4	40
Detecting a train on a track	Wbk 30	62
Diffraction	Wbk 4	6
Diffusion equation	Wbk 25	8, 14
Dimensional analysis	Wbk 47	2-23
Diode	Wbk 31	20
Divergence of a magnetic field	Wbk 28	43
Drag	Wbk 34	56
Drag	Wbk 47	15, 23
Dynamometer	Wbk 14	16
Earth horizon	Wbk 4	8
Elastic behaviour	Wbk 13	19
Electric circuit	Wbk 12	26
Electric circuit	Wbk 18	38
Electric circuit	Wbk 20	36. 44. 49
Electric current	Wbk 29	46
Electric current	Wbk 35	33, 39, 40
Electric current	Wbk 38	20
Electric current to screen	Wbk 41	24, 28, 35
Electric fan	Wbk 38	25
Electric field	Wbk 9	39-44
Electric field	Wbk 11	16
Electric field	Wbk 13	11
Electric field	Wbk 29	19, 63, 67, 68
Electric meters	Wbk 39	28
Electric motor	Wbk 29	27
Electric potential	Wbk 28	50
Electric wire	Wbk 33	10
Electrodynamometric meters	Wbk 14	16
Electromagnetic power	Wbk 6	50
Electromotive force	Wbk 11	21
Electron	Wbk 47	9
Electronic circuits	Wbk 3	69

Electronic component failure	Wbk 42	19
Electronic component lifetime	Wbk 46	6
Electronic filters	Wbk 12	2, 60
Electronic monitoring components	Wbk 42	5, 6
Electrostatic charge	Wbk 13	11
Electrostatic potential	Wbk 11	16
Electrostatics	Wbk 9	39-44
Electrostatics	Wbk 47	13
Energy	Wbk 14	13
Energy	Wbk 34	10, 28
Energy	Wbk 47	18
Engine power	Wbk 41	22
Equipotential curves	Wbk 26	14
Error in power to a load resistance	Wbk 18	38
Estimating the mass of a pipe	Wbk 3	27
Exponential decay of sound intensity	Wbk 6	46
Extension of spring	Wbk 43	21
Feedback applied to an amplifier	Wbk 10	26
Feedback convolution	Wbk 21	75
Field due to point charges	Wbk 9	40
Field strength around a charged line	Wbk 29	67
Field strength on a cylinder	Wbk 29	68
Flight overbooking	Wbk 39	29
Fluid flow	Wbk 26	36-37
Fluid flow	Wbk 48	80, 86, 91
Fluid power transmission	Wbk 12	31
Fluid theory	Wbk 47	14, 20
Force on a loop from an electric field	Wbk 29	27
Fraunhofer diffraction	Wbk 47	56, 60
Fuel injection system efficiency	Wbk 45	18
Fuel injection systems	Wbk 44	10
Fun ride - rollercoaster	Wbk 34	44
Fun ride - 'Rotor'	Wbk 34	46
Fun ride - 'Yankee Flyer'	Wbk 34	47
Gain	Wbk 10	26
Gauss' law	Wbk 29	63, 65
Harmonic oscillator	Wbk 23	69
Heat conduction	Wbk 48	76
Heat conduction equation	Wbk 25	8, 14
Heat conduction equation	Wbk 32	48
Heat conduction through a furnace wall	Wbk 25	32
Heat flow in an insulated metal plate	Wbk 1	85
Height of building	Wbk 18	34
Helmholtz's equation	Wbk 25	18

High frequency line equation	Wbk 25	16
Hooke's law	Wbk 43	21
Hooke's law	Wbk 47	6
Horizon distance	Wbk 4	8
Hydraulic brakes	Wbk 12	31
Hypertension and noise	Wbk 43	8
Ideal gas equation	Wbk 47	18
Ideal gas law	Wbk 18	13, 18
Ideal gas law and Redlich-Kwong equation	Wbk 18	18
Impedance	Wbk 12	60-63
Instant coffee production	Wbk 46	30, 32, 35
Insulating blocks	Wbk 45	4, 14, 29
Interference field	Wbk 47	51
Interference fringes	Wbk 47	64
Interference fringes	Wbk 4	31
Inverse square law decay of electromagnetic power	Wbk 6	50
Joukowski transformation	Wbk 26	19
Kepler's laws	Wbk 47	12
Kinetic energy	Wbk 1	79
Kinetic energy	Wbk 6	32
Kinetic energy	Wbk 34	10, 28
Kirchhoff's law	Wbk 3	10
Kirchhoff's law	Wbk 8	28-30
Kirchhoff's law	Wbk 20	49
Ladder network	Wbk 21	60
Laplace's equation	Wbk 25	7, 17, 25, 36
Laplace's equation	Wbk 26	11
Laplace's equation	Wbk 33	19, 27, 30, 34
Lifetime	Wbk 38	11, 13, 24, 25
Lift	Wbk 47	15
Light bulb lifetime	Wbk 46	5
Light bulbs	Wbk 38	11
Light ray propagation	Wbk 47	53
Light rays	Wbk 12	29
Light rays	Wbk 17	16
Light waves	Wbk 4	31
Light waves	Wbk 47	48
Light waves	Wbk 48	13
Lightning strike	Wbk 29	46
Lorentz force	Wbk 29	27

Mach number	Wbk 47	16
Magnetic field	Wbk 11	21
Magnetic field	Wbk 28	28, 43, 45
Magnetic field from a current line	Wbk 29	29
Magnetic flux	Wbk 13	51
Magnetic flux	Wbk 29	43
Magnets	Wbk 39	28
Manufacturing components	Wbk 35	48
Masses on spring	Wbk 20	47
Maximum height of projectile	Wbk 34	12
Maximum range of projectile	Wbk 34	14
Measuring the height of a building	Wbk 18	34
Metal bar temperature	Wbk 32	53-57, 60-64
Microphones	Wbk 48	10
Mixture - pressure in	Wbk 31	79-81
Modelling vibrating systems	Wbk 23	68
Models - beetles	Wbk 5	18
Models - carton	Wbk 5	33
Models - falling rock	Wbk 5	6-10, 26-30
Models - ferry	Wbk 5	18
Models - profit	Wbk 5	18, 30
Models - rain	Wbk 5	12
Models - rain level	Wbk 5	15
Models - road level	Wbk 5	14
Models - rocket	Wbk 5	10
Models - satellite	Wbk 5	10
Models - snowfall	Wbk 5	17
Models - sound	Wbk 5	46
Models - supply and demand	Wbk 5	21
Models - tide level	Wbk 5	39-44
Modulation	Wbk 4	40
Network	Wbk 1	52
Network	Wbk 7	4, 25-28
Newton's law of cooling	Wbk 32	3
Newton's laws of motion	Wbk 47	13
Newton's second law	Wbk 9	13
Newton's second law	Wbk 15	3
Newton's second law	Wbk 28	6
Newton's second law	Wbk 34	60
Noise	Wbk 43	8
Noise barriers	Wbk 4	6
Noise reduction by sound barriers	Wbk 4	6

Ohm's law	Wbk 3	25
Ohm's law	Wbk 29	47
Optical interference fringes due to glass plate	Wbk 4	31
Orbit	Wbk 17	22
Orifice plate flow meter	Wbk 47	20
Output signal	Wbk 20	64
Paint weathering	Wbk 44	29
Parabolic mirror	Wbk 47	27, 28, 29
Parachute	Wbk 6	48
Parachute	Wbk 34	58
Parallel design of components	Wbk 46	7-9
Pareto charts	Wbk 46	35
Pendulum	Wbk 47	7, 10-11
Pendulum	Wbk 48	50, 51
Pipe	Wbk 47	20
Pipe mass	Wbk 3	27
Piston ring diameter	Wbk 39	17
Planetary motion	Wbk 47	12
Plastic bottle design	Wbk 31	52
Plastic tube tensile strength	Wbk 44	47
Point - scratch resistance	Wbk 35	20
Point - shock resistance	Wbk 35	20
Poisson's equation	Wbk 25	18
Poisson's equation	Wbk 33	19, 28, 31
Population dynamic models	Wbk 32	8-11
Pressure	Wbk 9	4
Pressure	Wbk 27	3, 15, 36
Pressure	Wbk 47	16
Pressure in an ideal multicomponent mixture	Wbk 31	79
Pressure of gas	Wbk 18	13
Production line data	Wbk 46	27, 30, 32, 35, 36
Projectile	Wbk 4	47
Projectile - angled launch	Wbk 34	12
Projectile - energy	Wbk 34	10, 28
Projectile - height	Wbk 34	12
Projectile - horizontal launch	Wbk 34	9
Projectile - inclined plane	Wbk 34	30
Projectile - range	Wbk 34	14
Projectile - without air drag	Wbk 34	9
Propagation time difference	Wbk 47	53
Propellant	Wbk 45	6, 7, 16
Pulley belt tension	Wbk 14	8
Pumping engine bearing lifetime	Wbk 46	12-13

Quadratic resistance	Wbk 34	57, 59, 62
Quality control	Wbk 37	8
Quality control	Wbk 46	21-38
Radiation	Wbk 47	38, 41, 43, 46
Radiation emitted by microwave oven	Wbk 42	9
Radioactive decay	Wbk 27	58
Railway signals location	Wbk 48	72
Range of projectile	Wbk 34	12
Redlich-Kwong equation	Wbk 18	18
Refraction	Wbk 12	29
Refraction	Wbk 48	13
Relays	Wbk 41	10
Reliability in a communication network	Wbk 1	52
Reservoir	Wbk 27	42, 54
Resistance - linear	Wbk 34	56
Resistance - quadratic	Wbk 34	57, 59, 62
Resisted motion	Wbk 34	56-63
Reverberation	Wbk 6	46
Roadholding of car	Wbk 44	31
Rocket	Wbk 8	31
Rocket fuel shear strength	Wbk 45	6, 7, 16
Rollercoaster ride	Wbk 34	44
Roundabout	Wbk 34	36
Route network	Wbk 7	27
Sampling	Wbk 21	3, 85-95
Satellite motion	Wbk 48	60, 63
Schrödinger's equation	Wbk 25	18
Series design of components	Wbk 46	7, 9
Shear force and bending moment of a beam	Wbk 19	65
Shear strength	Wbk 43	18
Shear stress and strain	Wbk 13	19
Shot putting	Wbk 34	22
Signal sampling	Wbk 21	85-95
Simple harmonic motion	Wbk 4	68
Simple harmonic motion	Wbk 25	6
Skateboarding	Wbk 34	31
Skiing	Wbk 34	15
Snowflake falling	Wbk 48	56
Solenoid	Wbk 13	51
Solid rocket fuel	Wbk 45	6, 7, 16
Sonic boom	Wbk 14	12
Sound	Wbk 48	2, 7, 10
Sound intensity	Wbk 5	46
Sound intensity	Wbk 6	46
Sound waves	Wbk 4	6

Spot welds	Wbk 43	18
Spring	Wbk 43	21
Spring	Wbk 47	6
Spring - damped	Wbk 20	39
Springs	Wbk 20	47
Steel alloy corrosion	Wbk 44	21
Steel bar	Wkb 13	19
Steel cables	Wbk 41	25, 29, 37
Stiffness	Wbk 13	18
Strain	Wbk 8	10
Strain	Wbk 13	19
Strain gauge resistance	Wbk 39	18-20
Streamlines	Wbk 26	14
Stress	Wbk 8	10
Stress	Wbk 13	19
Stresses and strains on a section of material	Wbk 8	10
String	Wbk 47	5, 7
Submarine equation	Wbk 25	16
Surface tension	Wbk 47	14, 17
Suspended cable	Wbk 15	21
Suspended cable	Wbk 48	40
Switches	Wbk 41	10
System reliability	Wbk 46	7-9
System response	Wbk 20	71
Tank - ellipsoidal	Wbk 27	79
Tank - elliptic	Wbk 27	37
Telegraph equation	Wbk 25	16
Temperature of wire	Wbk 33	10
Tensile strength	Wbk 41	21
Tensile strength	Wbk 44	45, 47
Tension	Wbk 14	8
Tension in spring	Wbk 47	6
Tension in string	Wbk 47	7
Terminal velocity	Wbk 6	49
The current continuity equation	Wbk 29	46
The web-flange	Wbk 17	13
Thermal diffusivity	Wbk 32	46
Thermal insulation	Wbk 1	85
Tiddly-winks	Wbk 34	19
Tolerance limits	Wbk 46	24
Torque	Wbk 9	52
Torque	Wbk 13	19
Torque	Wbk 28	6
Torsion	Wbk 13	19
Torsion	Wbk 17	13
Torsion of mild-steel bar	Wbk 13	19

Total energy	Wbk 34	28
Traffic flow	Wbk 37	11, 46
Train on a track	Wbk 30	62
Transmission line equation	Wbk 25	16
Transverse vibrations equation	Wbk 25	18
Turbochargers	Wbk 41	17
Turbulence	Wbk 47	16
Two dimensional fluid flow	Wbk 26	36
Tyre mileage	Wbk 38	13
Undersea cable fault location	Wbk 3	25
van der Waals' equation	Wbk 47	18, 19, 23
Velocity of a rocket	Wbk 8	31
Velocity on a bend	Wbk 34	51
Vibrating system	Wbk 20	47
Vibration	Wbk 23	69
Vibration of string	Wbk 47	5
Vintage car brake pedal mechanism	Wbk 4	14
Viscosity	Wbk 47	14, 15, 16
Volume of liquid in an ellipsoidal tank	Wbk 27	79
Volume of liquid in an elliptic tank	Wbk 27	37
Washing machine faults	Wbk 42	20
Water flow	Wbk 47	20
Water height in an open channel	Wbk 48	45
Water wheel efficiency	Wbk 12	28
Waterflow	Wbk 28	12, 13, 25, 30
Wave equation	Wbk 32	70
Waves	Wbk 4	40-42
Waves	Wbk 47	17
Waves	Wbk 48	2, 7, 10
Wear on rollers	Wbk 40	11
Weathering of paint	Wbk 44	29
Woodscrew size variation	Wbk 40	6
Work done moving a charge in an electric field	Wbk 29	19
Young's modulus	Wbk 8	10
Young's modulus	Wbk 20	52

Mathematics Facts and Formulae

49.8

On the following pages are collections of useful Facts and Formulae. They were developed by Tony Croft and Geoff Simpson and are reproduced with the permission of Loughborough University Mathematics Education Centre.

Mathematical Topics

Algebra

Trigonometry

The Sine Rule and Cosine Rule

Hyperbolic Functions

Differentiation

Integration

Complex Numbers

Vectors

Sequences and Series

Matrices and Determinants

The Binomial Coefficients

Graphs of Common Functions

The Greek Alphabet

Algebra

$$(x+k)(x-k) = x^2 - k^2$$

$$(x+k)^2 = x^2 + 2kx + k^2, \quad (x-k)^2 = x^2 - 2kx + k^2$$

$$x^3 \pm k^3 = (x \pm k)(x^2 \mp kx + k^2)$$

Formula for solving a quadratic equation:

$$\text{if } ax^2 + bx + c = 0 \text{ then } x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Laws of Indices

$$a^m a^n = a^{m+n} \quad \frac{a^m}{a^n} = a^{m-n} \quad (a^m)^n = a^{mn}$$

$$a^0 = 1 \quad a^{-m} = \frac{1}{a^m} \quad a^{1/n} = \sqrt[n]{a} \quad a^{\frac{m}{n}} = (\sqrt[n]{a})^m$$

Laws of Logarithms

For any positive base b (with $b \neq 1$)

$$\log_b A = c \quad \text{means} \quad A = b^c$$

$$\log_b A + \log_b B = \log_b AB, \quad \log_b A - \log_b B = \log_b \frac{A}{B},$$

$$n \log_b A = \log_b A^n, \quad \log_b 1 = 0, \quad \log_b b = 1$$

Formula for change of base: $\log_a x = \frac{\log_b x}{\log_b a}$

Logarithms to base e , denoted \log_e or alternatively \ln are called *natural logarithms*. The letter e stands for the exponential constant which is approximately 2.718.

Partial fractions

For *proper fractions* $\frac{P(x)}{Q(x)}$ where P and Q are polynomials with the degree of P less than the degree of Q :

a *linear factor* $ax + b$ in the denominator produces a partial fraction of the form $\frac{A}{ax+b}$

repeated linear factors $(ax + b)^2$ in the denominator produce partial fractions of the form $\frac{A}{ax+b} + \frac{B}{(ax+b)^2}$

a *quadratic factor* $ax^2 + bx + c$ in the denominator produces a partial fraction of the form $\frac{Ax+B}{ax^2+bx+c}$

Improper fractions require an additional term which is a polynomial of degree $n - d$ where n is the degree of the numerator and d is the degree of the denominator.

Inequalities:

$$a > b \text{ means } a \text{ is greater than } b$$

$$a < b \text{ means } a \text{ is less than } b$$

$$a \geq b \text{ means } a \text{ is greater than or equal to } b$$

$$a \leq b \text{ means } a \text{ is less than or equal to } b$$

Trigonometry

Degrees and radians

$$360^\circ = 2\pi \text{ radians}, \quad 1^\circ = \frac{2\pi}{360} = \frac{\pi}{180} \text{ radians}$$

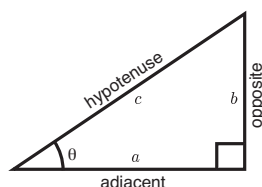
$$1 \text{ radian} = \frac{180}{\pi} \text{ degrees} \approx 57.3^\circ$$

Trig ratios for an acute angle θ :

$$\sin \theta = \frac{\text{side opposite to } \theta}{\text{hypotenuse}} = \frac{b}{c}$$

$$\cos \theta = \frac{\text{side adjacent to } \theta}{\text{hypotenuse}} = \frac{a}{c}$$

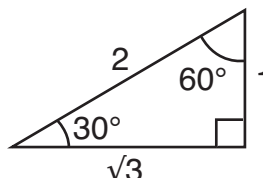
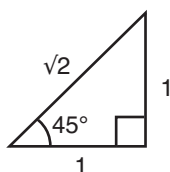
$$\tan \theta = \frac{\text{side opposite to } \theta}{\text{side adjacent to } \theta} = \frac{b}{a}$$



Pythagoras' theorem

$$a^2 + b^2 = c^2$$

Standard triangles:



$$\sin 45^\circ = \frac{1}{\sqrt{2}}, \quad \cos 45^\circ = \frac{1}{\sqrt{2}}, \quad \tan 45^\circ = 1$$

$$\sin 30^\circ = \frac{1}{2}, \quad \cos 30^\circ = \frac{\sqrt{3}}{2}, \quad \tan 30^\circ = \frac{1}{\sqrt{3}}$$

$$\sin 60^\circ = \frac{\sqrt{3}}{2}, \quad \cos 60^\circ = \frac{1}{2}, \quad \tan 60^\circ = \sqrt{3}$$

Common trigonometric identities

$$\sin(A \pm B) = \sin A \cos B \pm \cos A \sin B$$

$$\cos(A \pm B) = \cos A \cos B \mp \sin A \sin B$$

$$\tan(A \pm B) = \frac{\tan A \pm \tan B}{1 \mp \tan A \tan B}$$

$$2 \sin A \cos B = \sin(A + B) + \sin(A - B)$$

$$2 \cos A \cos B = \cos(A - B) + \cos(A + B)$$

$$2 \sin A \sin B = \cos(A - B) - \cos(A + B)$$

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

$$1 + \cot^2 A = \operatorname{cosec}^2 A, \quad \tan^2 A + 1 = \sec^2 A$$

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

$$\sin 2A = 2 \sin A \cos A$$

$$\sin^2 A = \frac{1 - \cos 2A}{2}, \quad \cos^2 A = \frac{1 + \cos 2A}{2}$$

$\sin^2 A$ is the notation used for $(\sin A)^2$. Similarly $\cos^2 A$ means $(\cos A)^2$ etc. This notation is used with trigonometric and hyperbolic functions but with positive integer powers only.

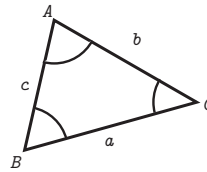
The sine rule and cosine rule

The sine rule

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C}$$

The cosine rule

$$a^2 = b^2 + c^2 - 2bc \cos A$$



Hyperbolic functions

$$\cosh x = \frac{e^x + e^{-x}}{2}, \quad \sinh x = \frac{e^x - e^{-x}}{2}$$

$$\tanh x = \frac{\sinh x}{\cosh x} = \frac{e^x - e^{-x}}{e^x + e^{-x}}$$

$$\operatorname{sech} x = \frac{1}{\cosh x} = \frac{2}{e^x + e^{-x}}$$

$$\operatorname{cosech} x = \frac{1}{\sinh x} = \frac{2}{e^x - e^{-x}}$$

$$\operatorname{coth} x = \frac{\cosh x}{\sinh x} = \frac{1}{\tanh x} = \frac{e^x + e^{-x}}{e^x - e^{-x}}$$

Hyperbolic identities

$$e^x = \cosh x + \sinh x, \quad e^{-x} = \cosh x - \sinh x$$

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

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

$$\operatorname{coth}^2 x - 1 = \operatorname{cosech}^2 x$$

$$\sinh(x \pm y) = \sinh x \cosh y \pm \cosh x \sinh y$$

$$\cosh(x \pm y) = \cosh x \cosh y \pm \sinh x \sinh y$$

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

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

$$\cosh^2 x = \frac{\cosh 2x + 1}{2}$$

$$\sinh^2 x = \frac{\cosh 2x - 1}{2}$$

Inverse hyperbolic functions

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

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

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

Differentiation

$y = f(x)$	$\frac{dy}{dx} = f'(x)$
k , constant	0
x^n , any constant n	nx^{n-1}
e^x	e^x
$\ln x = \log_e x$	$\frac{1}{x}$
$\sin x$	$\cos x$
$\cos x$	$-\sin x$
$\tan x = \frac{\sin x}{\cos x}$	$\sec^2 x$
$\operatorname{cosec} x = \frac{1}{\sin x}$	$-\operatorname{cosec} x \cot x$
$\sec x = \frac{1}{\cos x}$	$\sec x \tan x$
$\cot x = \frac{\cos x}{\sin x}$	$-\operatorname{cosec}^2 x$
$\sin^{-1} x$	$\frac{1}{\sqrt{1-x^2}}$
$\cos^{-1} x$	$\frac{-1}{\sqrt{1-x^2}}$
$\tan^{-1} x$	$\frac{1}{1+x^2}$
$\cosh x$	$\sinh x$
$\sinh x$	$\cosh x$
$\tanh x$	$\operatorname{sech}^2 x$
$\operatorname{sech} x$	$-\operatorname{sech} x \tanh x$
$\operatorname{cosech} x$	$-\operatorname{cosech} x \coth x$
$\coth x$	$-\operatorname{cosech}^2 x$
$\cosh^{-1} x$	$\frac{1}{\sqrt{x^2-1}}$
$\sinh^{-1} x$	$\frac{1}{\sqrt{x^2+1}}$
$\tanh^{-1} x$	$\frac{1}{1-x^2}$

The linearity rule for differentiation

$$\frac{d}{dx}(au + bv) = a\frac{du}{dx} + b\frac{dv}{dx} \quad a, b \text{ constant}$$

The product and quotient rules for differentiation

$$\frac{d}{dx}(uv) = u\frac{dv}{dx} + v\frac{du}{dx} \quad \frac{d}{dx}\left(\frac{u}{v}\right) = \frac{v\frac{du}{dx} - u\frac{dv}{dx}}{v^2}$$

The chain rule for differentiation

If $y = y(u)$ where $u = u(x)$ then $\frac{dy}{dx} = \frac{dy}{du} \cdot \frac{du}{dx}$

For example,

if $y = (\cos x)^{-1}$, $\frac{dy}{dx} = -1(\cos x)^{-2}(-\sin x)$

Integration

$f(x)$	$\int f(x) dx = F(x) + c$	
k , constant	$kx + c$	
x^n , ($n \neq -1$)	$\frac{x^{n+1}}{n+1} + c$	
$x^{-1} = \frac{1}{x}$	$\begin{cases} \ln x + c & x > 0 \\ \ln(-x) + c & x < 0 \end{cases}$	
e^x	$e^x + c$	
$\cos x$	$\sin x + c$	
$\sin x$	$-\cos x + c$	
$\tan x$	$\ln(\sec x) + c$	$-\frac{\pi}{2} < x < \frac{\pi}{2}$
$\sec x$	$\ln(\sec x + \tan x) + c$	$-\frac{\pi}{2} < x < \frac{\pi}{2}$
$\operatorname{cosec} x$	$\ln(\operatorname{cosec} x - \cot x) + c$	$0 < x < \pi$
$\cot x$	$\ln(\sin x) + c$	$0 < x < \pi$
$\cosh x$	$\sinh x + c$	
$\sinh x$	$\cosh x + c$	
$\tanh x$	$\ln \cosh x + c$	
$\operatorname{coth} x$	$\ln \sinh x + c$	$x > 0$
$\frac{1}{x^2+a^2}$	$\frac{1}{a} \tan^{-1} \frac{x}{a} + c$	$a > 0$
$\frac{1}{x^2-a^2}$	$\frac{1}{2a} \ln \frac{x-a}{x+a} + c$	$ x > a > 0$
$\frac{1}{a^2-x^2}$	$\frac{1}{2a} \ln \frac{a+x}{a-x} + c$	$ x < a$
$\frac{1}{\sqrt{x^2+a^2}}$	$\sinh^{-1} \frac{x}{a} + c$	$a > 0$
$\frac{1}{\sqrt{x^2-a^2}}$	$\cosh^{-1} \frac{x}{a} + c$	$x \geq a > 0$
$\frac{1}{\sqrt{x^2+k}}$	$\ln(x + \sqrt{x^2+k}) + c$	
$\frac{1}{\sqrt{a^2-x^2}}$	$\sin^{-1} \frac{x}{a} + c$	$-a \leq x \leq a$
$f(ax + b)$	$\frac{1}{a} F(ax + b) + c$	$a \neq 0$
e.g. $\cos(2x - 3)$	$\frac{1}{2} \sin(2x - 3) + c$	

The linearity rule for integration

$$\int (af(x) + bg(x)) dx = a \int f(x) dx + b \int g(x) dx, \quad (a, b \text{ constant})$$

Integration by substitution

$$\int f(u) \frac{du}{dx} dx = \int f(u) du \quad \text{and} \quad \int_a^b f(u) \frac{du}{dx} dx = \int_{u(a)}^{u(b)} f(u) du$$

Integration by parts

$$\int_a^b u \frac{dv}{dx} dx = [uv]_a^b - \int_a^b \frac{du}{dx} v dx$$

Alternative form:

$$\int_a^b f(x)g(x) dx = [f(x) \int g(x) dx]_a^b - \int_a^b \frac{df}{dx} \{ \int g(x) dx \} dx$$

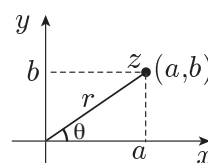
Complex Numbers

Cartesian form: $z = a + bj$ where $j = \sqrt{-1}$

Polar form:

$$z = r(\cos \theta + j \sin \theta) = r \angle \theta$$

$$a = r \cos \theta, \quad b = r \sin \theta, \quad \tan \theta = \frac{b}{a}$$



Exponential form: $z = re^{j\theta}$

Euler's relations

$$e^{j\theta} = \cos \theta + j \sin \theta, \quad e^{-j\theta} = \cos \theta - j \sin \theta$$

Multiplication and division in polar form

$$z_1 z_2 = r_1 r_2 \angle (\theta_1 + \theta_2), \quad \frac{z_1}{z_2} = \frac{r_1}{r_2} \angle (\theta_1 - \theta_2)$$

If $z = r \angle \theta$, then $z^n = r^n \angle (n\theta)$

De Moivre's theorem

$$(\cos \theta + j \sin \theta)^n = \cos n\theta + j \sin n\theta$$

Relationship between hyperbolic and trig functions

$$\cos jx = \cosh x, \quad \sin jx = j \sinh x$$

$$\cosh jx = \cos x, \quad \sinh jx = j \sin x$$

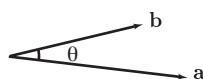
i rather than j may be used to denote $\sqrt{-1}$.

Vectors

If $\mathbf{r} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$ then $|\mathbf{r}| = \sqrt{x^2 + y^2 + z^2}$

Scalar product

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

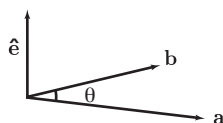


If $\mathbf{a} = a_1\mathbf{i} + a_2\mathbf{j} + a_3\mathbf{k}$ and $\mathbf{b} = b_1\mathbf{i} + b_2\mathbf{j} + b_3\mathbf{k}$ then

$$\mathbf{a} \cdot \mathbf{b} = a_1 b_1 + a_2 b_2 + a_3 b_3$$

Vector product

$$\mathbf{a} \times \mathbf{b} = |\mathbf{a}| |\mathbf{b}| \sin \theta \hat{\mathbf{e}}$$



$\hat{\mathbf{e}}$ is a unit vector perpendicular to the plane containing \mathbf{a} and \mathbf{b} in a sense defined by the right hand screw rule.

If $\mathbf{a} = a_1\mathbf{i} + a_2\mathbf{j} + a_3\mathbf{k}$ and $\mathbf{b} = b_1\mathbf{i} + b_2\mathbf{j} + b_3\mathbf{k}$ then

$$\begin{aligned} \mathbf{a} \times \mathbf{b} &= (a_2 b_3 - a_3 b_2)\mathbf{i} + (a_3 b_1 - a_1 b_3)\mathbf{j} + (a_1 b_2 - a_2 b_1)\mathbf{k} \\ &= \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \end{vmatrix} \end{aligned}$$

Sequences and Series

Arithmetic progression: $a, a + d, a + 2d, \dots$

a = first term, d = common difference,

k th term = $a + (k - 1)d$

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

Sum of the first n integers,

$$1 + 2 + 3 + \dots + n =$$

$$\sum_{k=1}^n k = \frac{1}{2}n(n + 1)$$

Sum of the squares of the first n integers,

$$1^2 + 2^2 + 3^2 + \dots + n^2 =$$

$$\sum_{k=1}^n k^2 = \frac{1}{6}n(n + 1)(2n + 1)$$

Geometric progression: a, ar, ar^2, \dots

a = first term, r = common ratio,

k th term = ar^{k-1}

Sum of n terms, $S_n = \frac{a(1-r^n)}{1-r}$, provided $r \neq 1$

Sum of an infinite geometric series:

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

The binomial theorem

If n is a positive integer

$$(1 + x)^n = 1 + nx + \frac{n(n-1)}{2!}x^2 + \frac{n(n-1)(n-2)}{3!}x^3 + \dots + x^n$$

When n is negative or fractional, the series is infinite and converges when $-1 < x < 1$

Standard power series expansions

$$e^x = 1 + \frac{x}{1!} + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots \text{ for all } x$$

$$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \dots \text{ for all } x$$

$$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \dots \text{ for all } x$$

$$\log_e(1 + x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \dots \text{ for } -1 < x \leq 1 \text{ only}$$

The exponential function as the limit of a sequence

$$\lim_{n \rightarrow \infty} \left(1 + \frac{x}{n}\right)^n = e^x$$

Matrices and Determinants

The 2×2 matrix $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ has determinant

$$|A| = \begin{vmatrix} a & b \\ c & d \end{vmatrix} = ad - bc$$

The 3×3 matrix $A = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}$ has determinant

$$|A| = a_{11} \begin{vmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{vmatrix} - a_{12} \begin{vmatrix} a_{21} & a_{23} \\ a_{31} & a_{33} \end{vmatrix} + a_{13} \begin{vmatrix} a_{21} & a_{22} \\ a_{31} & a_{32} \end{vmatrix}$$

(expanded along the first row).

The inverse of a 2×2 matrix

If $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ then $A^{-1} = \frac{1}{ad-bc} \begin{pmatrix} d & -b \\ -c & a \end{pmatrix}$

provided that $ad - bc \neq 0$.

Matrix multiplication: for 2×2 matrices

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} \alpha & \gamma \\ \beta & \delta \end{pmatrix} = \begin{pmatrix} a\alpha + b\beta & a\gamma + b\delta \\ c\alpha + d\beta & c\gamma + d\delta \end{pmatrix}$$

Remember that $AB \neq BA$ except in special cases.

The Binomial Coefficients

The coefficient of x^k in the binomial expansion of $(1+x)^n$ when n is a positive integer is denoted by $\binom{n}{k}$ or ${}^n C_k$.

$$\binom{n}{k} = \frac{n!}{k!(n-k)!} = \binom{n}{n-k}$$

$0! = 1$, $n! = n(n-1)!$

so, for example, $4! = 1.2.3.4$

The pattern of the coefficients is seen in

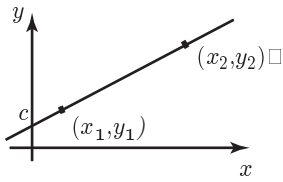
Pascal's triangle:

$$\begin{array}{ccccccc} & & & & 1 & & 1 & \\ & & & & & 1 & & 1 & \\ & & & 1 & & 2 & & 1 & \\ & & 1 & & 3 & & 3 & & 1 & \\ & 1 & & 4 & & 6 & & 4 & & 1 & \\ 1 & & 5 & & 10 & & 10 & & 5 & & 1 & \\ \vdots & & \vdots & & \vdots & & \vdots & & \vdots & & \vdots & \end{array}$$

${}^n C_k$ is the number of subsets with k elements that can be chosen from a set with n elements.

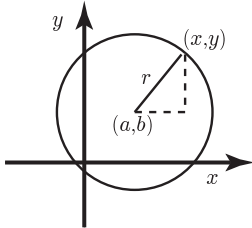
Graphs of Common Functions

Linear $y = mx + c$, m =gradient, c = vertical intercept



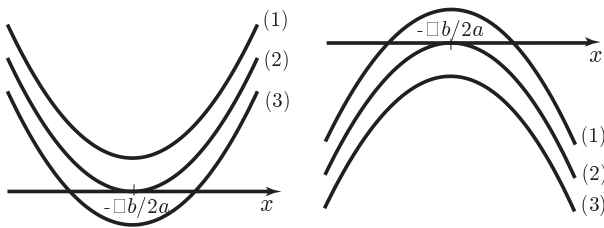
$$m = \frac{y_2 - y_1}{x_2 - x_1}$$

The equation of a circle centre (a, b) , radius r



$$(x - a)^2 + (y - b)^2 = r^2$$

Quadratic functions $y = ax^2 + bx + c$



- | | | | |
|-----|-----------------|-----|-----------------|
| | $a > 0$ | | $a < 0$ |
| (1) | $b^2 - 4ac < 0$ | (1) | $b^2 - 4ac > 0$ |
| (2) | $b^2 - 4ac = 0$ | (2) | $b^2 - 4ac = 0$ |
| (3) | $b^2 - 4ac > 0$ | (3) | $b^2 - 4ac < 0$ |

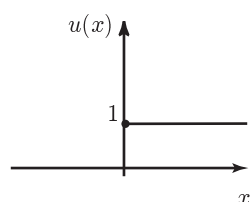
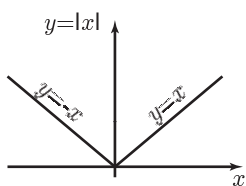
Completing the square

$$\text{If } a \neq 0, \quad ax^2 + bx + c = a \left(x + \frac{b}{2a} \right)^2 + \frac{4ac - b^2}{4a}$$

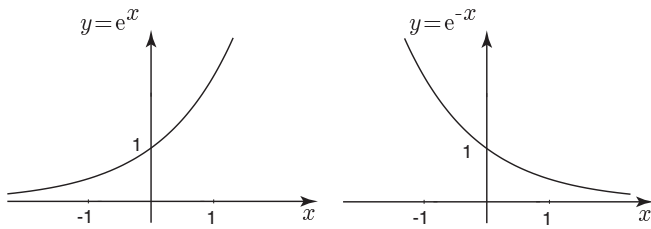
The modulus function

The unit step function, $u(x)$

$$|x| = \begin{cases} x & \text{if } x \geq 0 \\ -x & \text{if } x < 0 \end{cases} \quad u(x) = \begin{cases} 1 & \text{if } x \geq 0 \\ 0 & \text{if } x < 0 \end{cases}$$

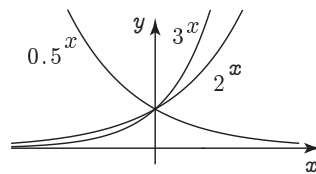


Exponential functions



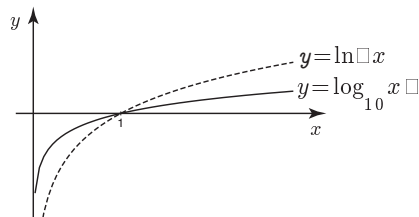
Graph of $y = e^x$ showing exponential growth

Graph of $y = e^{-x}$ showing exponential decay



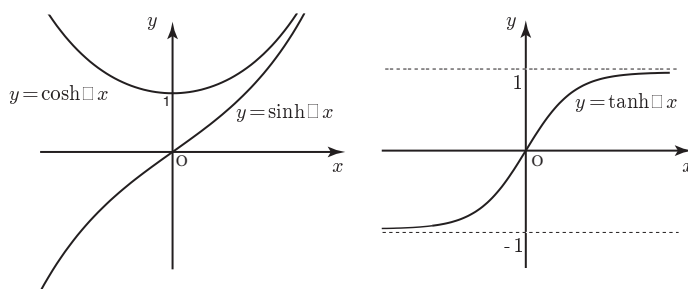
Graphs of $y = 0.5^x$, $y = 3^x$, and $y = 2^x$

Logarithmic functions



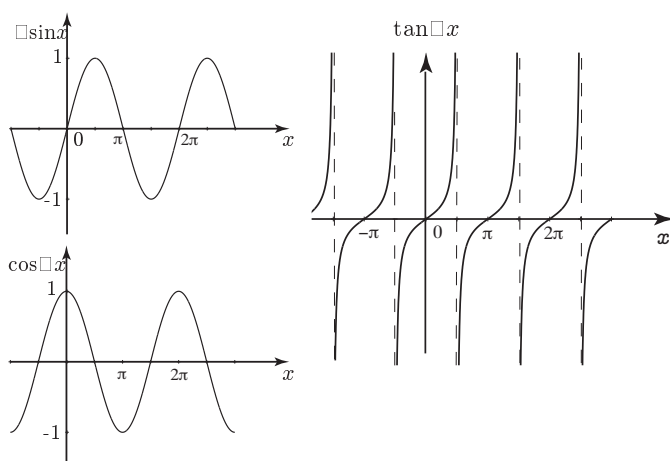
Graphs of $y = \ln x$ and $y = \log_{10} x$

Hyperbolic functions



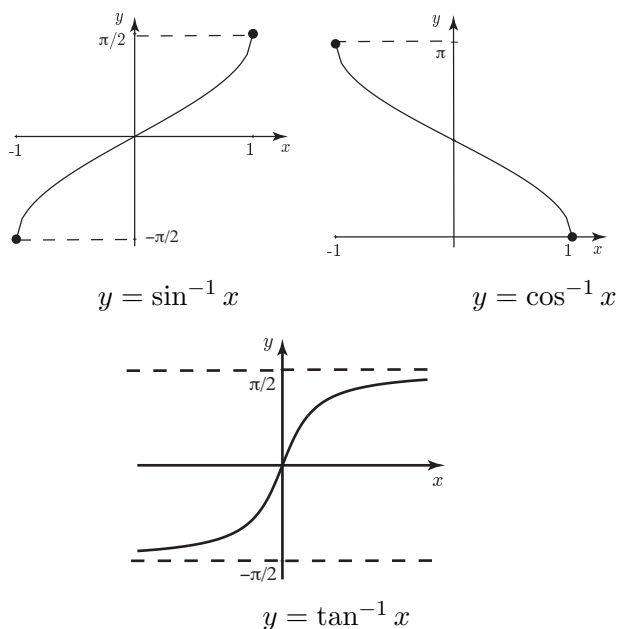
Graphs of $y = \sinh x$, $y = \cosh x$ and $y = \tanh x$

Trigonometric functions



The sine and cosine functions are periodic with period 2π . The tangent function is periodic with period π .

Inverse trigonometric functions



The Greek alphabet

<i>A</i>	α	alpha	<i>I</i>	ι	iota	<i>P</i>	ρ	rho
<i>B</i>	β	beta	<i>K</i>	κ	kappa	Σ	σ	sigma
Γ	γ	gamma	Λ	λ	lambda	<i>T</i>	τ	tau
Δ	δ	delta	<i>M</i>	μ	mu	Υ	υ	upsilon
<i>E</i>	ϵ	epsilon	<i>N</i>	ν	nu	Φ	ϕ	phi
<i>Z</i>	ζ	zeta	Ξ	ξ	xi	<i>X</i>	χ	chi
<i>H</i>	η	eta	<i>O</i>	o	omicron	Ψ	ψ	psi
Θ	θ	theta	Π	π	pi	Ω	ω	omega