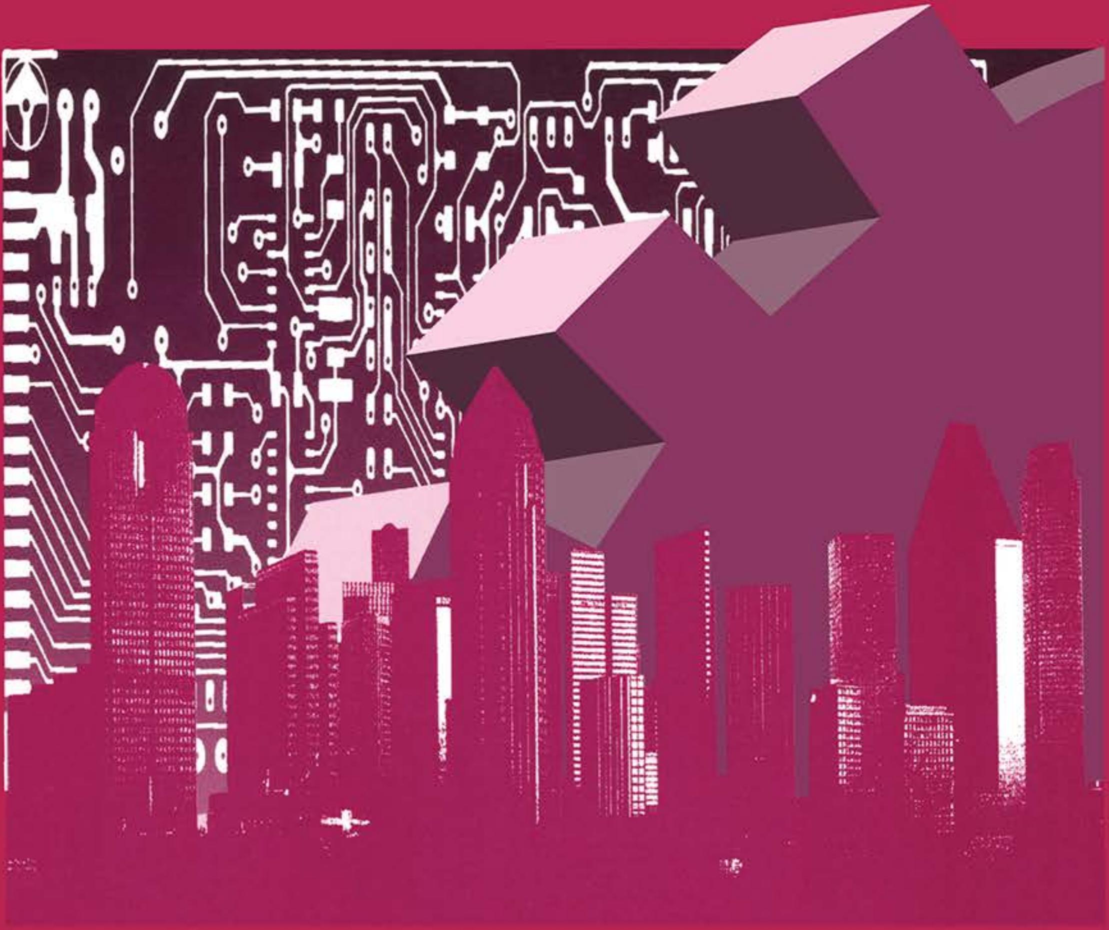
FOUNDATION SCIENCE FOR ENGINEERS



KEITH L. WATSON

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CONTENTS

PART 3: ELECTRICITY AND MAGNETISM

PREFACE

This book has been written for students without science A-levels who are entering an engineering degree or Higher National Diploma course via a foundation year. Very little scientific background is assumed and only an elementary knowledge of mathematics, which need extend no further than the simple properties of the right-angled triangle. Calculus is not required.

The book is divided into three parts, which may be taken either in series or in parallel. Emphasis has been placed on clarity and crispness of presentation, and on the provision of appropriate worked examples and practice questions. (The data supplied are approximate and are for illustrative purposes only.)

I have selected those topics which seem to me to provide the essential core material for any engineering foundation course. Practical work is not covered: the inclusion of instructions for safe and effective laboratory exercises over the whole range of topics would have lengthened the book considerably, and, furthermore, the needs of individual courses and the resources of individual institutions tend to determine their particular selection of specific exercises.

I am indebted to many colleagues here at Portsmouth for advice and comments on various parts of the manuscript; in particular, I should like to thank Dr Ray Batt, Professor Trevor Crabb, Michael Devane, Derek Hunter, Dr Tom Nevell, Bob Otter, Ron Parvin and Vic Riches — also Professor Brian Lee for his support. I am especially grateful to Kerry Lawrence of The Macmillan Press for her patience and encouragement, and to Professor John Wilson of the University of Northumbria at Newcastle, who reviewed the manuscript and made many helpful suggestions. Last, but not least, I thank my wife for her powers of endurance.

Portsmouth, 1992 KLW

Part 1

Force, Matter and Motion

TOPIC 1 QUANTITIES

COVERING:

- SI units;
- base and derived units;
- scalar and vector quantities;
- vector addition.

1.1 SI UNITS

Engineering quantities (pressure, temperature, power, and so on) need to be expressed in terms of an agreed system of units. SI units (Système International d'Unités) have been adopted in the UK and in many other countries, so we shall use them in this book. The system is founded on seven base units and two supplementary units from which all the others are derived.

The base units which are going to be of most interest to us are shown in Table 1.1 together with some of the derived units. We shall add to the list as we go along.

Derived units can be construed in terms of independent dimensions (such as length, mass and time) that are provided by the base units. Let us consider the unit of power as an illustration. Don't worry if you are unable to follow the scientific arguments too well at this stage. We shall go over them much more thoroughly later. The important thing to appreciate is that we can analyse the relationship between quantities in terms of their constituent base units.

First, velocity is a measure of change of position in unit time and its magnitude is given in metres per second ($\mathrm{m\ s^{-1}}$). Acceleration is a measure of the rate at which velocity changes and its magnitude is given in metres per second per second ($\mathrm{m\ s^{-2}}$).

The unit of force is called the *newton* (N). As we shall see later, it is defined as the force needed to give a mass of 1 kg an acceleration of 1 $\mathrm{m\ s^{-2}}$. The relationship between these quantities is given by $F = ma$, where F represents force, m represents mass and a represents acceleration. The constituent base units of force are therefore those of mass times acceleration and

$$1\ \mathrm{N} = 1\ \mathrm{kg\ m\ s^{-2}}$$

Table 1.1

	Name	Symbol
Some base units:		
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin	K
(For our purposes °C = K − 273: see Topic 16)		
Some derived units:		
Force	newton	N
Energy	joule	J
Power	watt	W
Pressure	pascal	Pa
Electric charge	coulomb	C

Taking this a step further, the *joule* (J) is the SI unit of energy. This is equal to the amount of work done when the point of application of a force of 1 newton moves through a distance of 1 metre in the direction of the force. If W is the work done and s is the distance moved in the direction of the force F, then $W = Fs$. The constituent base units of energy are therefore those of force times distance and

$$1\ \mathrm{J} = 1\ \mathrm{kg\ m^2\ s^{-2}}$$

Finally, power is the rate at which work is done or energy expended. The SI unit of power is called the *watt* (W), which corresponds to a rate of 1 joule per second. The base units of power are therefore those of energy divided by time and

$$1\ \mathrm{W} = 1\ \mathrm{kg\ m^2\ s^{-3}}$$

So, starting with the base units of mass, length and time, we have derived the unit of power.

Units often require prefixes to adjust them to an appropriate scale of magnitude for a particular measurement. For instance, we use *kilo*metres (km, a thousand metres) for large distances and *milli*metres (mm, a thousandth of a metre) for small ones. Table 1.2 shows the prefixes that we shall be using in this book.

1.2 SCALAR AND VECTOR QUANTITIES

Scalar quantities are those that are completely specified by their magnitude (e.g. length, speed and mass) and can be manipulated

Table 1.2

Prefix	Symbol	Factor	
giga-	G	× 10^9	(a thousand million)
mega-	M	× 10^6	(a million)
kilo-	k	× 10^3	(a thousand)
deci-	d	× 10^{-1}	(a tenth)
centi-	c	× 10^{-2}	(a hundredth)
milli-	m	× 10^{-3}	(a thousandth)
micro-	μ	× 10^{-6}	(a millionth)
nano-	n	× 10^{-9}	(a thousand millionth)
pico-	p	× 10^{-12}	(a million millionth)

by simple arithmetic operations such as addition and multiplication. *Vector* quantities have both magnitude and direction (e.g. displacement, velocity and force). This makes them more complicated to handle, because angles are involved.

Let us start with displacement, i.e. change of position. This can be defined in terms of distance in a particular direction. But, as we can see from the example in Figure 1.1, there is another approach. Figure 1.1(a) shows a displacement of 5 units at an angle of 37° measured anticlockwise from the positive x-axis (i.e. from the 3 o'clock direction). Figure 1.1(b) shows the same displacement as the *resultant* of moving a distance of 4 units in the 0° direction, then 3 units in the 90° direction. Since tan 37° = 3/4 and, from Pythagoras' theorem, $5 = \sqrt{4^2 + 3^2}$, we can see that both methods give the same result.

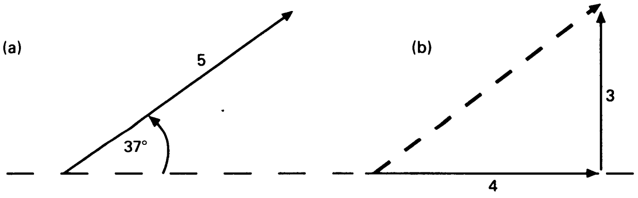

Figure 1.1

Vector quantities are often expressed in terms of distances and angles as in Figure 1.1(a), but sometimes we need to *resolve* them into perpendicular components as in Figure 1.1(b). From the figure we can see that the vertical component, equal to 3, is given by 5 sin 37 and the horizontal component, equal to 4, is given by 5 cos 37. This is useful when we need to find the resultant of two vector quantities.

For example, Figure 1.2(a) shows a displacement OA at an angle α followed by a second displacement AB at an angle β. Figure 1.2(b) shows the resultant OB in the direction θ. The total vertical displacement y is equal to (OA sin α + AB sin β) and the total horizontal displacement x is equal to (OA cos α + AB cos β). So, knowing the magnitude and direction of the two original displacements, we can

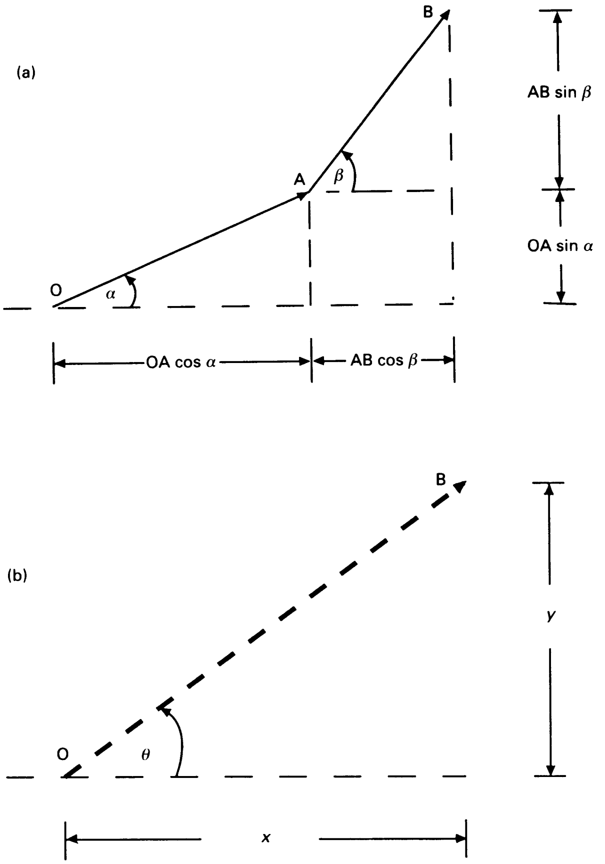

Figure 1.2

calculate y and x. We can then calculate the magnitude of OB from Pythagoras' theorem and its direction from $\tan \theta = y/x$.

Clearly we can use this method to obtain the resultant of as many displacements as we wish by plotting vectors head to tail. If the vectors form a closed loop, then the resultant (hence, the net displacement) is zero. Taking Figure 1.2 as an illustration, if we travelled from O to A, then from A to B, and finally from B back to O, the three displacement vectors would form a closed triangle and we would end up where we started. This is an obvious but important idea that we shall need to use later.

Note that velocity is a measure of displacement in unit time and that it is a vector quantity that can be manipulated in the same way as displacement. Later we shall use similar methods to handle forces.

Before tackling the questions at the end of the topic, make sure that you understand the following worked examples. And remember that, unless stated otherwise, angles are measured anticlockwise from the positive x-axis.

Worked Example 1.1

Find the magnitude and direction of the resultant of a displacement of 103 m at 62° followed by another of 59 m at 28°.

The displacements are shown in Figure 1.3.

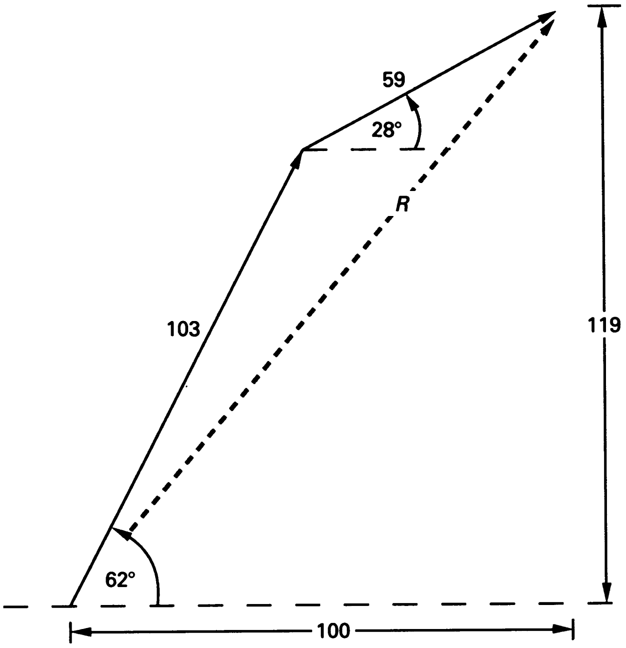

Figure 1.3

The total vertical displacement is equal to

$103 \sin 62 + 59 \sin 28 = 119$ m

The total horizontal displacement is equal to

$103 \cos 62 + 59 \cos 28 = 100$ m

The magnitude of the resultant R is equal to

$\sqrt{119^2 + 100^2} = 155$ m

The direction of the resultant R is equal to

$\tan^{-1} 119/100 = 50°$

Worked Example 1.2

Find the magnitude and direction of the resultant of successive displacements of 25 m at 90°, 30 m at 45° and 20 m at 300°.

The displacements are shown in Figure 1.4.

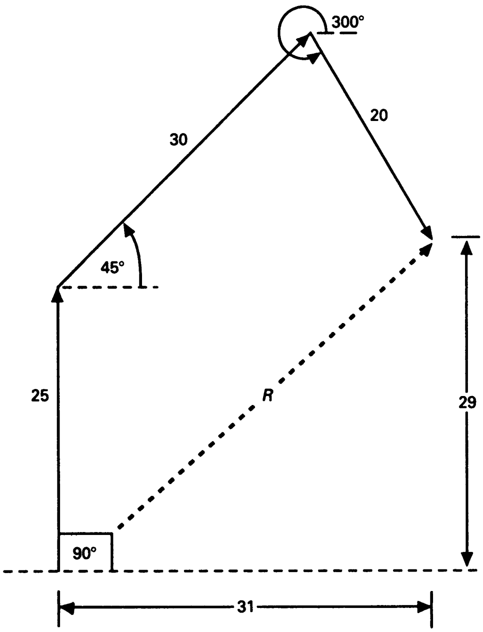

Figure 1.4

The total vertical displacement is equal to

$$25 \sin 90 + 30 \sin 45 + 20 \sin 300 = 29 \text{ m}$$

The total horizontal displacement is equal to

$$25 \cos 90 + 30 \cos 45 + 20 \cos 300 = 31 \text{ m}$$

The magnitude of the resultant R is equal to

$$\sqrt{29^2 + 31^2} = 42 \text{ m}$$

The direction of the resultant R is equal to

$$\tan^{-1} 29/31 = 43°$$

Worked Example 1.3

If a boat is being rowed due north at 2 m s^{-1} and there is a current flowing due east at 1.5 m s^{-1}, what is the true velocity of the boat relative to the earth?

The velocity diagram is shown in Figure 1.5. The magnitude of the resultant R is equal to

$$\sqrt{2^2 + 1.5^2} = 2.5 \text{ m s}^{-1}$$

The direction of the resultant R is equal to

$$\tan^{-1}\frac{1.5}{2} = 37° \text{ east of north}$$

i.e. 53° anticlockwise from the positive x-axis.

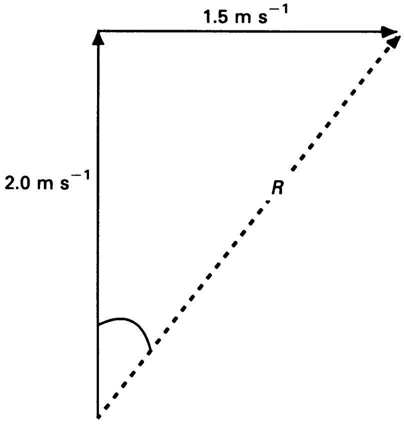

Figure 1.5

Questions

1. Find the magnitude and direction of the resultants of the following pairs of successive displacements:
   (a) 42 m at 31°, 53 m at 72°;
   (b) 117 m at 28°, 67 m at 147°;
   (c) 331 m at 47°, 158 m at 238°;
   (d) 97 m at 72°, 84 m at 163°.
2. A car climbs a hill at a road speed of 10 m s^{-1}. If the slope of the hill is 6° above the horizontal, what are the horizontal and vertical components of the car's velocity?
3. An object travels eastwards at 5 m s^{-1} for 7 s, then northwards at 7.5 m s^{-1} for 12 s, then westwards at 10 m s^{-1} for 15 s. Find how far and in what direction it must travel to return to its starting point.
4. A ship steers north at 5.0 m s^{-1} with a current flowing towards the south-east at 2.0 m s^{-1}. With what velocity must a man cross the deck to maintain a fixed position relative to the seabed?
5. An object travels 52 m in the 1 o'clock direction, then 71 m in the 5 o'clock direction, then 103 m in the 8 o'clock direction, then 43 m in the 11 o'clock direction. What is its resultant displacement?
6. A boat heads due north across a river 300 m wide which