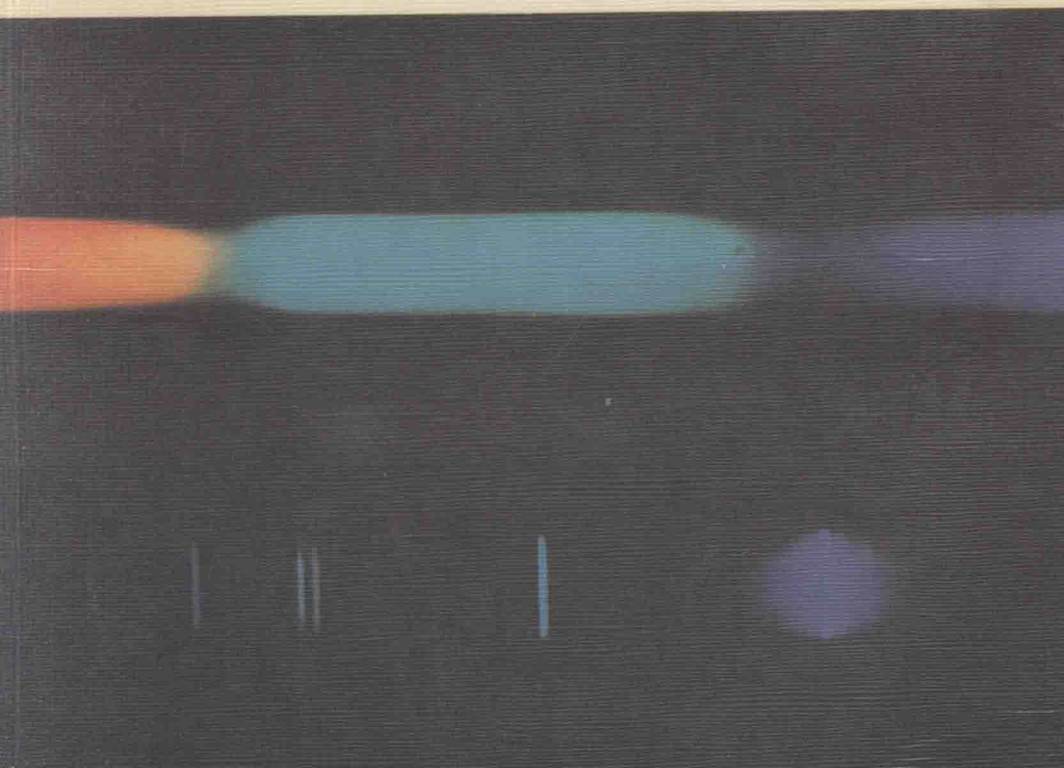
ESSENTIALS OF HIGHER PHYSICS

Mary Webster



Essentials of Higher Physics

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H·E·B

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Preface

This book contains a succinct and cogent coverage of the material required for the Scottish Higher Physics examination.

The uses of this book are twofold: firstly, it can be used throughout the year as a précis of the material required for each topic. The text could be employed directly by teachers in order to alleviate the problem of providing each student with satisfactory notes. Accordingly more time could then be devoted to experiments, discussions, and problems. Secondly, it provides the basis for constructive revision prior to an examination. An adequate summary of principles, equations, and formulae is given in the framed sections. A useful reminder of important details may be obtained by reading all sentences commencing '*Note:*'.

Problems are given at the end of each lettered section in order that skill may be achieved in modes of solution and to highlight further certain aspects of the section. Detailed solutions are provided at the end of the book. Naturally these problems are in no way to be regarded as a substitute for questions from past examination papers. To accentuate the need for continual practice in problem solving an exercise section with brief answers is included.

SI units are employed throughout.

I should like to thank all those who have helped in the preparation of this book; especially certain students for their pertinent questions, my colleague Mr. George Maxwell, and the publishers for their assistance. I am particularly grateful to Mr. J. L. Patterson for so carefully reading and editing the manuscript and providing many excellent suggestions and improvements. Finally, a special note of gratitude is due to my husband, Brian Webster, for his continual encouragement.

1978 M.W.

Contents

1 Mechanics

A: Units, Dimensions, Scalars, and Vectors, and Measurement

1:A.1 *SI System of Units*

When any quantity is measured its **unit** must be stated. A length of 17 has no meaning. For a unit, such as the metre, to be accepted and understood by scientists throughout the world a standard 'metre' had to be agreed upon. In Paris, in 1960, an International Committee proposed the SI system of units (Système International D'Unites), which has seven **basic units** corresponding to seven **independent** physical quantities.

Quantity	length	mass	time	electric current	thermodynamic temperature	amount of substance
Unit	metre	kilogram	second	ampere	kelvin	mole

(The seventh basic unit, the **candela**, is the unit of luminous intensity and does not require discussion in this book.)

These basic units are defined in terms of a particular property of a given substance. As examples, the definitions of the units of length, mass, and time are given below.

Length: metre
This used to be based on a platinum–iridium rod kept in Paris. It is now defined in terms of the wavelength of a particular spectral line of krypton, ^{86}Kr.

$$1 \text{ metre} = 1\,650\,763.73 \text{ wavelengths of this radiation}$$

Mass: kilogram
Defined as the mass of a piece of platinum–iridium kept under standard conditions at Sèvres, near Paris, France.

Time: second
This used to be based on the mean solar day. It is now defined in terms of the period of a particular radiation emitted by caesium, ^{133}Cs.

$$1 \text{ second} = 9\,192\,631\,770 \text{ periods}$$

The **ampere** is defined in terms of the current required by two specified conductors to produce a certain force (see Section 3:B.1).

For interest it may be noted that the **kelvin** is defined in terms of the temperature at which steam, water, and ice may co-exist, this point being termed the triple point of water. Then a temperature scale based on the two fixed points for melting ice and boiling water may be established.

The **mole** is discussed later (see Section 2:A.2).*

Basic units used in this text, with their abbreviations:

metre (m)	kilogram (kg)	second (s)
ampere (A)	kelvin (K)	mole (mol)

Units for other quantities are termed **derived units**, as they may be obtained by a simple combination of the above units, *without numerical* factors.

Examples: A velocity of one metre per second is that velocity possessed by an object when its displacement increases by one metre in every second. Hence the unit for velocity is $m\ s^{-1}$.

A unit of energy would be $kg\ m^2\ s^{-2}$ but for convenience this is abbreviated to the joule, J.

The specific heat capacity of a substance has a unit of $J\ kg^{-1}\ K^{-1}$.

In terms of basic units, potential difference would have a unit of $kg\ m^2\ s^{-3}\ A^{-1}$ which is called the volt, V.

Common prefixes

m – 10^{-3} (milli)	μ – 10^{-6} (micro)	n – 10^{-9} (nano)
p – 10^{-12} (pico)	k – 10^{3} (kilo)	M – 10^{6} (mega)

1:A.2 *Dimensions*

The dimension of a quantity is an algebraic symbol assigned to a quantity independent of its units.

Example: The distance between stars in light years; the wavelength of light in nm; the height of a man in metres; these are all length quantities with dimensions [L].

For mechanics and electricity there are four essential dimensions:

Length [L], Mass [M], Time [T], Current [I].

All other mechanical and electrical quantities may be expressed in terms of these four dimensions.

Examples: Momentum – $[M][L][T]^{-1}$ Charge – [I][T]
sin θ – no dimensions, as it is a ratio of the lengths of two sides of a right-angled triangle.

1:A.3 *Scalars and Vectors*

A quantity is a **scalar** if it has magnitude only.

Example: The length of a piece of paper; the energy used by a light bulb.

* Memorization of the details of the SI system of units is not necessary.

A quantity is a **vector** if it has magnitude and direction.

Example: The force of gravity on a book lying on a table is downwards; the momentum of a moving car is forwards (unless in reverse gear!); an electric field will send electrons in a certain direction only.

Addition of scalars

Two scalar quantities may be added or subtracted arithmetically providing the units are the same.

Example:	3 cm + 10 cm = 13 cm
but	2 inches + 7 cm = (2 × 2.54) + 7 cm

Addition of vectors

With vector quantities account must be taken of their *directions*.

Example: Two forces of 4 N and 2 N are pushing an object. The angle between the two forces is 60°, see Figure 1.1(a). Determine the total force.

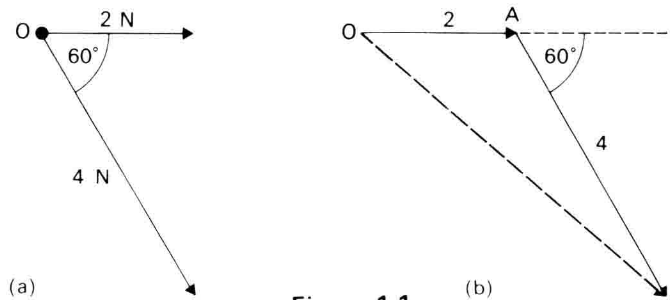


Figure 1.1

The direction of the forces are shown by the arrows. The vector sum of these forces may be obtained by construction, as in Figure 1.1(b). OA is 2 units long and AB is 4 units long. Notice the position of the 60° angle.

The resultant total force, or vector sum, is OB which may be measured. The angle AÔB will give its direction.

$$OB = 5.3 \text{ units} \qquad A\hat{O}B = 41°$$

Thus the resultant force has a magnitude of 5.3 N and acts in a direction of 41° to the 2 N force.

Note: The arrow on AB follows on from the arrow on OA. They must *not* be in opposing directions. (The head to tail rule.)

The same process may be applied for a number of vectors.

Example: Three forces **a**, **b**, and **c** act on a body at a point O (Figure 1.2(a)).

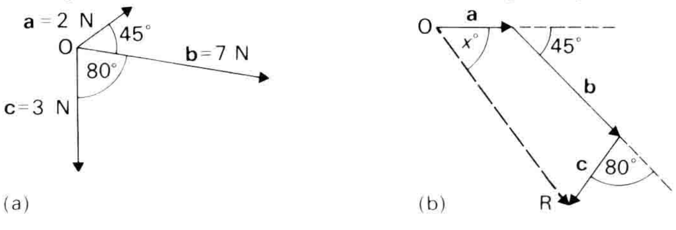
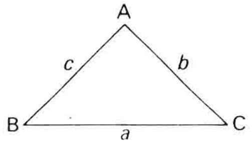


Figure 1.2

The resultant force, or vector sum, is obtained by construction (Figure 1.2(b)). The magnitude is given by OR and acts in a direction x from **a**.

Resultant force = 9 N at an angle of 55° from **a**.

In some simple cases it is easy to calculate the vector sum, particularly when right angles are involved. (For the more mathematically inclined the cosine and sine rules can be used for any triangle namely;



$$c^2 = a^2 + b^2 - 2ab\cos C \text{ and } \frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C}.)$$

Components of a vector

Two vectors may be added together to give a single resultant vector. *Conversely*, a single vector may be split into two vectors which equal that single vector. These two vectors are usually chosen to be at right angles to each other.

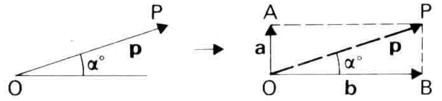


Figure 1.3 Components of a vector

The vector sum of **a** + **b** is equal to the vector **p**, see Figure 1.3(b).

$$\overrightarrow{OB} + \overrightarrow{BP} = \overrightarrow{OP} \qquad BP = \mathbf{a}$$
$$\mathbf{b} + \mathbf{a} = \mathbf{p}$$

a and **b** are the right angled **components** of vector **p**.
p is said to have been **resolved** into the two components **a** and **b**.

Magnitude of **b** = OP cos α
Magnitude of **a** = OP sin α $\qquad A\hat{P}O = \alpha$

Example: What are the horizontal and vertical components of a 20 N force acting at 30° to the horizontal (Figure 1.4)?

Magnitude of the horizontal component, **b** = 20 cos 30° = $10\sqrt{3}$ N
Magnitude of the vertical component, **a** = 20 sin 30° = 10 N

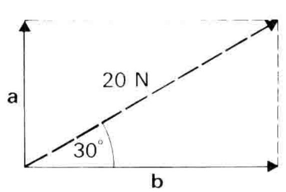


Figure 1.4

1:A.4 *Measurement*

In any experimental determination or demonstration the factors affecting the accuracy of the measurement should be considered. These include:

(1) Limitations of the instrument in use: an ammeter of 0–10 A range with 1 A graduations can only give readings to about the nearest 0.2 A.

(2) Choice of instrument or design of the experiment: a stop watch is a poor device for timing a weight dropped from a table to the floor!

(3) Personal errors: starting and stopping a stop watch.

For every physical quantity encountered the following should be known:

(1) Its common unit.
(2) If it is a scalar or a vector.
(3) Its mode of measurement.

Problem

1.1 Determine the dimensions of: force, power, potential difference, frequency, focal length of a lens, linear magnification of an object by a lens, half life of a radioactive isotope.

B: *Time, Velocity, and Acceleration*

1:B.1 *Time*

Unit: second (s), scalar.

Measured by a stop watch, electronic clock, or scalar, ticker timer, or by 'stopping' a periodic motion with a stroboscope.

Stroboscopes

Mechanical: motor- or hand-driven disc with one or more equally-spaced slits.
Light: a regularly flashing light.

The rate of revolution, or flashing, is adjusted until the periodic motion viewed, for example of water waves or a rotating handle, is stationary. The number of flashes per second, or the rate of revolution R for a single slit disc, will equal the frequency of the motion viewed. For a stroboscope with N slits, the frequency is N times R, as the motion or object will be seen as each slit takes the place of the previous one.

If the rate of revolution or flashing is doubled (or tripled) then the motion or object will be seen twice (or three times). This is called double (or triple) viewing.

If the rate is halved then single viewing is still obtained but the motion or object is only viewed every other cycle. Thus the correct frequency for the motion is the *highest single-viewing frequency*.

1:B.2 *Distance, Displacement, Speed, and Velocity*

Distance

Unit: metre (m), scalar.

> Distance is the total length along a specified path.

Example: A bird flies 6 km east then 3 km north. Its total flight distance is 9 km.

Displacement

Unit: metre (m), vector.

> The displacement of an object is the length and direction of a line drawn from a starting point to the final position of that object.

Example: A man walks from A to B by the path shown in Figure 1.5. If the length of AB is 3.5 km then the displacement from A is 3.5 km, 78° E of N.

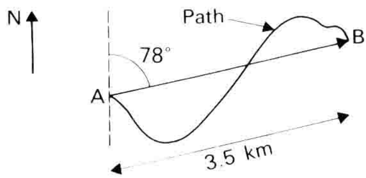


Figure 1.5

Example: A man travels 20 km north, 6 km east, and 12 km north-east. What is his distance and displacement from his starting point?

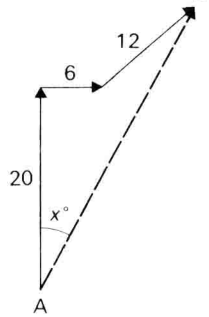


Figure 1.6

His displacement is the length AB at an angle x° E of N (Figure 1.6). By construction these may be measured, giving his displacement as 32 km, 27° E of N.

His distance is $20 + 6 + 12 = 38$ km.

Speed

Unit: m s^{-1}, scalar.
Speed is the rate at which an object moves.

$$\text{Speed} = \frac{\text{distance covered}}{\text{time taken}}$$

$$\text{Average speed} = \frac{\text{total distance}}{\text{total time}}$$

Velocity

Unit: m s^{-1}, vector.
Velocity is the rate at which an object moves in a certain direction.

For a *constant velocity*:

$$\text{Velocity} = \frac{\text{displacement}}{\text{time taken}}$$

When the *velocity is changing*:

$$\text{Velocity} = \frac{\text{small displacement}}{\text{time taken for that small displacement}}$$

Ideally the time interval should approach zero.

Both speed and velocity may be measured by determining the time taken for a given distance or displacement to be covered. If the velocity is changing the time interval should be small so a ticker timer or light beam/photocell and scalar arrangement must be used. With the latter arrangement the object whose velocity is to be determined interrupts a narrow light beam directed on to a photocell. The electric clock or scalar connected to the photocell only records the time when the light does *not* reach the photocell. Thus, if a clock records a time of 0.36 s when an object of diameter (or length) 2.7 cm passes through the light beam, the velocity of the object is $\frac{2.7}{0.36} = 0.75$ cm s^{-1}. The drag or friction on the tape of a ticker timer limits the accuracy of its use for determining speed or velocity. Multiple-flash photography may be used for more accurate velocity determinations.

For a *uniformly changing* velocity and *linear* motion.

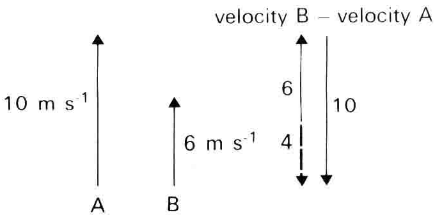
$$\text{average velocity} = \tfrac{1}{2}\,(\text{initial velocity} + \text{final velocity})$$

Note: The difference between speed and velocity: speed is a scalar quantity with magnitude only; a negative velocity implies a reverse direction.

Relative velocity

To determine the relative velocity of a moving object A with respect to another moving object B, the velocity of B must be subtracted from that of A. (This is equivalent to bringing B to rest by subtracting the velocity of B from both A and B.)

Example: An object A travels due north at 10 m s^{-1} and passes another object B also moving north at 6 m s^{-1}. The velocity of A relative to B is (10 − 6) = 4 m s^{-1} due north. Notice that the velocity of B relative to A is 4 m s^{-1} due south, i.e. −4 m s^{-1} north, see Figure 1.7.



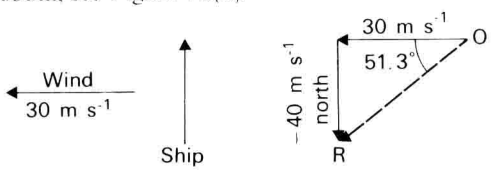
(a) (b) **Figure 1.7**

Sometimes the objects are travelling in different directions.

Example: What is the relative velocity of a wind blowing due west at 30 m s^{-1} to a person standing on a ship moving north at 40 m s^{-1}?

The velocity of the ship must be subtracted (vectorially) from the velocity of the wind.

Subtraction of a vector 40 m s^{-1} north is equivalent to adding a vector of 40 m s^{-1} south, see Figure 1.8(b).

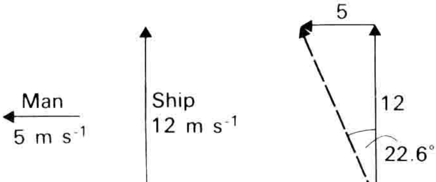


(a) (b) **Figure 1.8**

To a person on the ship the wind appears to have a velocity of magnitude OR = 50 m s^{-1} in a direction 53.1° S of W.

A common problem in physics examinations is when two objects are moving relative to a third.

Example: A man walks across the deck of a ship at 5 m s^{-1} due west with respect to the ship. The ship is moving at 12 m s^{-1} north with respect to the sea. Determine the man's velocity relative to the *sea*.



(a) (b) **Figure 1.9**

Here the *sum* of these two velocities is required, namely 13 m s^{-1} in a direction 22.6 W of N, see Figure 1.9.

1:B.3 *Acceleration*

Unit: m s^{-2}, vector.
Acceleration is the rate at which the velocity is changing.

For a *uniform acceleration*:

$$\text{Acceleration} = \frac{\text{change in velocity}}{\text{time taken for that change}}$$

For a *non-uniform acceleration* the time interval should be as small as possible, tending to zero.

Note: The acceleration should be stressed as being the change in velocity with *time* and not with distance. It is the change in velocity which takes place in one second.

For a *uniform acceleration* and *linear motion*:

u – initial velocity v – final velocity
a – acceleration t – time taken
s – displacement

$$a = \frac{v - u}{t}$$

which is

$$v = u + at \qquad (1)$$

For a uniform acceleration:

$$\text{Average velocity} = \tfrac{1}{2}(u + v) \qquad \text{and also} = \frac{s}{t}$$

which together give

$$s = \tfrac{1}{2}t\,(u + v)$$

Using $v = u + at$ and substituting for v,

$s = \frac{1}{2}t\,(u + u + at)$

$$s = ut + \tfrac{1}{2}at^2 \qquad (2)$$

Eliminating t from (1) and (2) gives

$$v^2 = u^2 + 2as \qquad (3)$$

These three equations are called the **equations of motion.**

$$v = u + at \qquad s = ut + \tfrac{1}{2}at^2 \qquad v^2 = u^2 + 2as$$

and providing

(1) the acceleration is uniform and the motion is linear,
(2) the units are correct, and
(3) the acceleration is given a negative sign for a deceleration,

any unknown quantity may be calculated from these three equations.

Example: List the quantities given in the question below with their units and add to the list the quantity to be calculated. Then choose that equation containing those four quantities.

A ball accelerates at 5 m s^{-2} from rest for 4 s. What distance has it travelled?

$a = +5$ m s^{-2} (There is no information about the final velocity nor is its calculation required so it is not included in the list.)
$u = 0$
$t = 4$ s
$s = ?$

Check that the units are consistent and a has the correct sign.

The equation required is $s = ut + \frac{1}{2}at^2$.

$s = 0 + \frac{1}{2} \times 5 \times 16$

Distance, $s = 40$ m

1:B.4 *Graphs of Acceleration a, Velocity v, Displacement s, with Time t*

Interpretation of graphs

When two quantities are plotted against each other the **gradient** (or slope) of the graph obtained is the rate at which one quantity (usually the ordinate y) varies with respect to the other (usually the abscissa x).

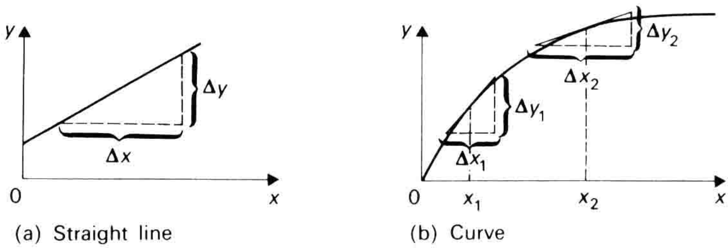


Figure 1.10 Gradients

The gradient is the ratio $\frac{\Delta y}{\Delta x}$.

Note: If the graph is a straight line the gradient $\frac{\Delta y}{\Delta x}$ is constant. If the graph is a curve the tangent to the curve at the point of interest is drawn and the gradient $\frac{\Delta y}{\Delta x}$ determined for that point. In Figure 1.10(b), the gradient at x_2 is *less* than that at x_1, showing that the gradient is decreasing.

Graphs for linear motion

(1) **No acceleration:** constant velocity

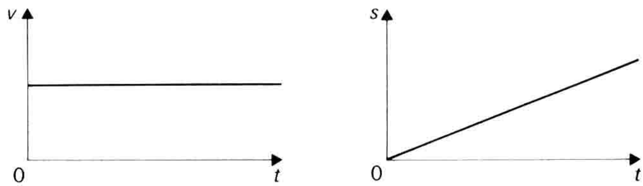


Figure 1.11

(2) **Constant acceleration**

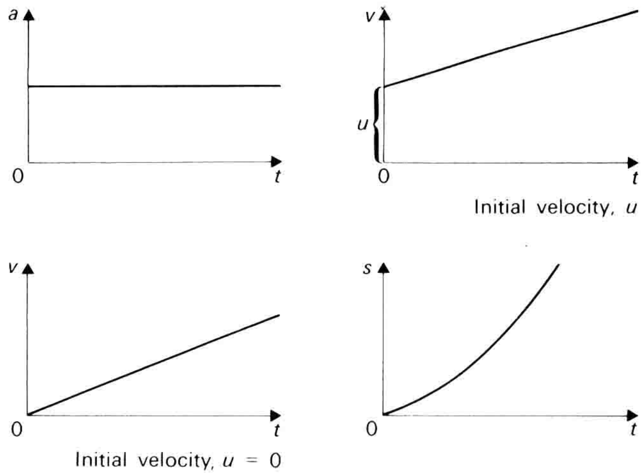


Figure 1.12

(3) **Constant deceleration**

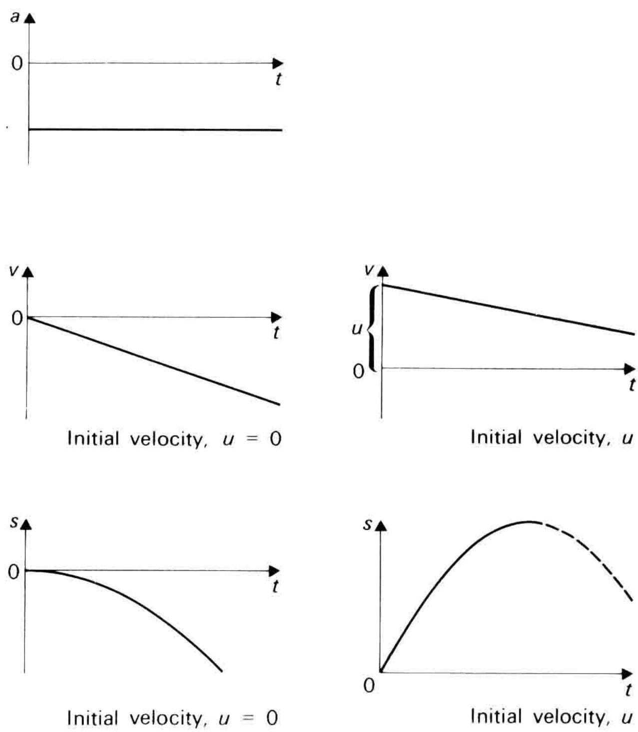


Figure 1.13