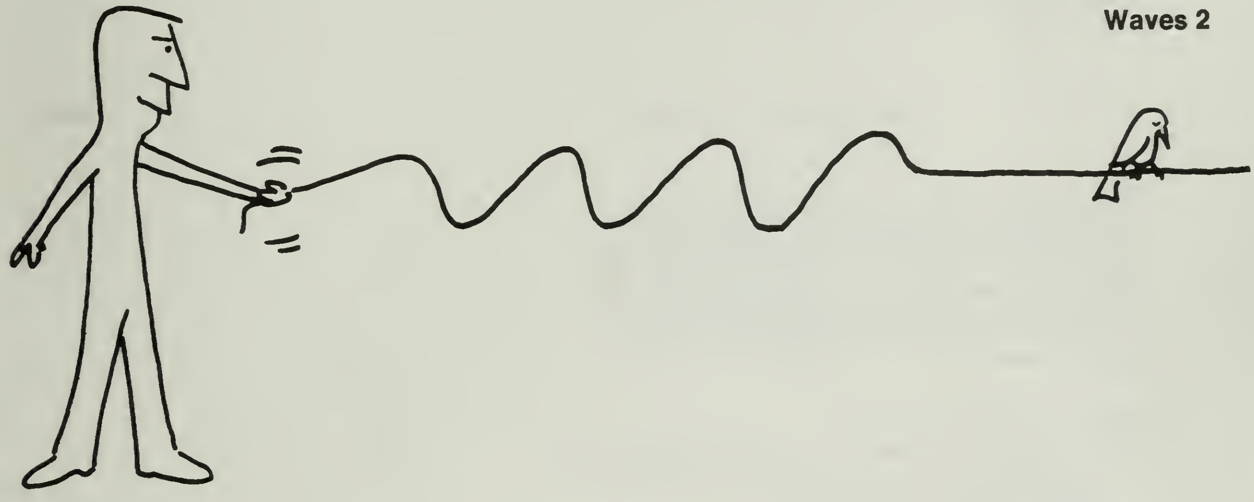
The Project Physics Course

Programmed Instruction

Waves 1

Waves 2



The Kinetic-Molecular Theory of Gases

INTRODUCTION

You are about to use a programmed text. You should try to use this booklet where there are no distractions—a quiet classroom or a study area at home, for instance. Do not hesitate to seek help if you do not understand some problem. Programmed texts require your active participation and are designed to challenge you to some degree. Their sole purpose is to teach, not to quiz you.

In this book there are three separate programs. The first, Waves 1, proceeds from left to right across the top part of the book. Waves 2 parallels it, starting at the front of the book again, and using the middle portion of each page. The third program, Kinetic-Molecular Theory, takes up the bottom part of each page. It can be studied either before or after the two wave programs.

This publication is one of the many instructional materials developed for the Project Physics Course. These materials include Texts, Handbooks, Teacher Resource Books, Readers, Programmed Instruction Booklets, Film Loops, Transparencies, 16mm films and laboratory equipment. Development of the course has profited from the help of many colleagues listed in the text units.

Directors of Project Physics
Gerald Holton, Department of Physics, Harvard University
F. James Rutherford, Chairman, Department of Science Education, New York University
Fletcher G. Watson, Harvard Graduate School of Education

ISBN: 0-03-089643-6
012 008 9876

A Component of the Project Physics Course

Distributed by
Holt, Rinehart and Winston, Inc.
New York — Toronto

Cover Art by Andrew Ahlgren

Waves 1 The Superposition Principle

Knowledge of the behavior of waves is of basic importance in physics. In this program you will learn something about brief wave disturbances—pulses: how they travel, and what happens when two pulses pass through the same region at the same time.

Waves 2 Periodic Waves

When the same wave shape is repeated over and over again, the wave is called a *periodic* wave. In this program you will learn the relationships among the frequency, period, wavelength, and speed of a periodic wave.

Kinetic-Molecular Theory of Gases

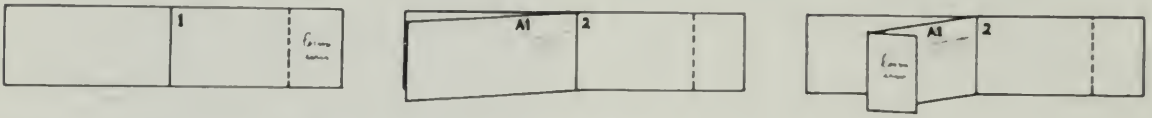
This program consists of a series of problems that will help you to understand the kinetic molecular theory and the behavior of gases. Following most problems is a hint (printed upside down below the dashed line). In the answer frames the solutions to the problems are worked out in detail. To derive the most benefit from this program, make a reasonable effort to solve each problem without help. If success does not come, read the hint. If you still have trouble, look at the solution, then go back and work through the problem yourself.

The problem sequence used in this program is adapted from:
Physics For the Enquiring Mind
Eric M. Rogers
Princeton University Press, 1960

INSTRUCTIONS

1. *Frames:* Each frame contains a question. Answer the question by writing in the blank space next to the frame. Frames are numbered 1, 2, 3, . . .

2. *Answer Blocks:* To find an answer to a frame, turn the page. Answer blocks are numbered A1, A2, A3, . . . This booklet is designed so that you can compare your answer with the given answer by folding back the page, like this:



3. Always write your answer *before* you look at the given answer.

4. If you get the right answers to the sample questions, you do not have to complete the program.

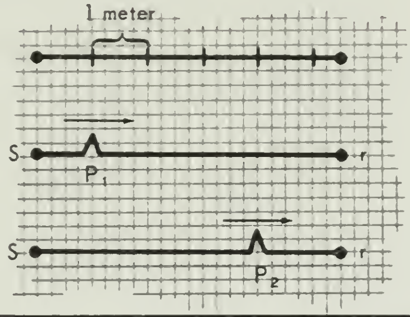
INSTRUCTIONS: Same as for Waves 1 above.

INSTRUCTIONS: Same as for Waves 1 above.

Sample Question A

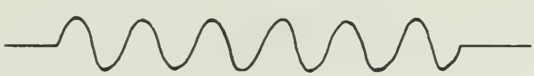
The disturbance travels from P_1 to P_2 in a time Δt.

If Δt = 1.0 seconds, what is the speed at which the disturbance travels?



Sample Question A

The waves on the diagram were produced in 1.5 seconds.



What is the frequency f in cycles per second?

Turn page to begin the program

The Kinetic-Molecular Theory of Gases

Answer to A

$$v = \frac{\Delta d}{\Delta t}$$

$\Delta d = 3.0$ m

$\Delta t = 1.0$ sec

$$v = \frac{3.0 \text{ m}}{1.0 \text{ sec}} = 3.0 \text{ m/sec}$$

Answer to A

$$\frac{6.0 \text{ cycles}}{1.5 \text{ sec}} = 4.0 \text{ cycles/sec}$$

In developing the kinetic-molecular theory of gases, we use elastic collisions of balls as a model, and find results that correspond to the observed behavior of gases. So, for that set of phenomena, we consider invisible molecules as though they were perfectly elastic spheres. The theory may seem difficult at first, but if you carry it through once, thinking about it carefully, it will soon begin to make good sense.

Sample Question B

The diagram shows two pulses traveling towards each other along a rope. An instant later the pulses arrive at Point P, the center of the rope. What is the maximum displacement of the rope at that instant?

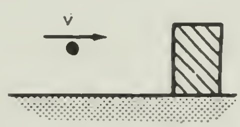
Sample Question B

The frequency of a wave is the number of (i) ____________________ that pass a point per (ii) ____________________, and is equal to the inverse of the (iii) ________________.

1

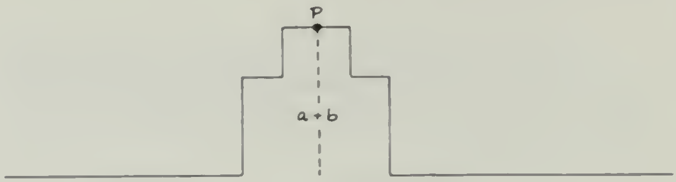
A ball of mass 2.0 kg moving 12 m/sec to the right hits a massive wall head-on and stops dead.

The momentum of the ball *before* impact is ______ ______
(units)



Hint: Recall that momentum equals mass times velocity.

Answer to B



Maximum displacement is a + b. If you missed this or Sample Question A, you can profit by working through this program booklet, beginning with Question 1. If you got Sample Questions A and B right, go on to Sample Question C.

Answer to B

(i) cycles (complete waves)

(ii) second

(iii) period

A1

$\vec{p} = m\vec{v}$

$m = 2.0\ kg$

$\vec{v} = +12\ m/sec$

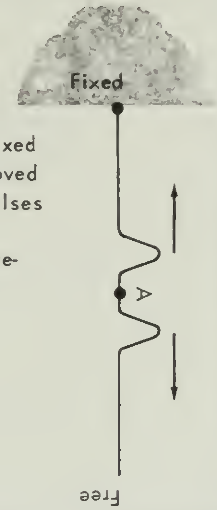
$\vec{p} = (2.0\ kg)(+12\ m/sec)$

$$\boxed{\vec{p} = +24\ \frac{kg \cdot m}{sec}}$$

Sample Question C

A rope is hung as in the diagram, one end fixed and the other end free. At point A the rope is moved sideways and bock suddenly, creating similar pulses that travel towards the ends.

Sketch what the pulses will look like after reflection from the ends.



Sample Question C

If waves of frequency $f = 20$ cycles per second travel with speed $v = 40$ meters per second in a given medium,

(i) what is the wavelength of the waves in the medium?

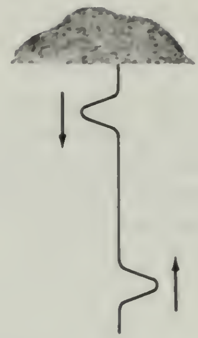
(ii) what is the period of the waves?

2

Since the ball stops dead when it strikes the wall, the momentum of the ball *after* impact is ______ ______ (units).

Hint: In this inelastic collision, the velocity of the ball after impact is zero.

Answer to C



If you got this question right also, you need not complete Waves 1. Turn instead to the Project Physics Programmed Instruction booklet Waves 2. If you missed Sample Question C (but got A and B right) begin this program at question 16.

Answer to C

(i) $\lambda = \frac{v}{f}$

$= \frac{40 \text{ m/sec}}{20 \text{ cycles/sec}}$

$\lambda = 2.0 \text{ m/cycle}$

(ii) $T = \frac{1}{f} = \frac{1}{20}$ sec/cycle

$T = .05$ sec/cycle

A2

$\vec{p}' = m'\vec{v}'$

$m' = 2.0$ kg

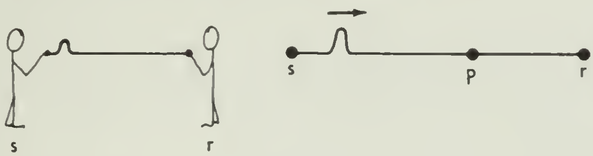
$\vec{v}' = 0.0$ m/sec

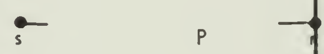
$\vec{p}' = (2.0 \text{ kg})(0.0 \text{ m/sec})$

$$\boxed{\vec{p}' = 0.0 \frac{\text{kg} \cdot \text{m}}{\text{sec}}}$$

1

Two people hold opposite ends of a rope. The sender, s, snaps his end of the rope, creating a disturbance that travels along the rope towards the receiver, r.





A short time (Δt) later, the disturbance passes point P.

Draw the disturbance as it passes P.

Sample Question D

The figure shows an attentuated (domped) periodic wave.

Of the following, which property is changing?
speed of wave, wavelength, amplitude,
frequency, period.

3

If the momentum of the ball before impact was +24 kg · m/sec, and the momentum after impact was 0.0 kg · m/sec, then the *change of momentum* that the ball underwent is ______ ______ (units).

Hint: Change of momentum equals momentum after impact minus momentum before impact.

$$\Delta \vec{p} = \vec{p}' - \vec{p}.$$

A1

Answer to D

Only amplitude is changing.

If you were able to answer all of the sample questions correctly, the rest of the program is optional.

A3

$$\Delta\vec{p} = \vec{p}\,' - \vec{p}$$

$$\vec{p}\,' = 0.0 \, \frac{\text{kg} \cdot \text{m}}{\text{sec}}$$

$$\vec{p} = +24 \, \frac{\text{kg} \cdot \text{m}}{\text{sec}}$$

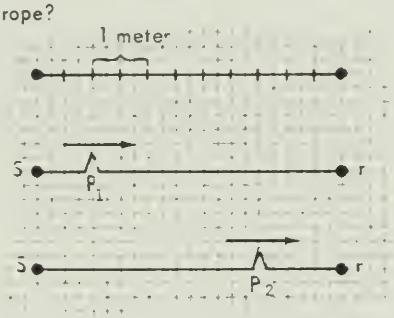
$$\Delta\vec{p} = (0.0 - 24) \, \frac{\text{kg} \cdot \text{m}}{\text{sec}}$$

$$\boxed{\Delta\vec{p} = -24 \, \frac{\text{kg} \cdot \text{m}}{\text{sec}}}$$

2

The disturbance below travels through the rope from P_1 to P_2 in a time Δt.

If $\Delta t = 1.0$ seconds, what is the speed at which the disturbance travels in the rope?

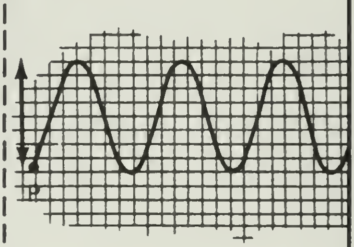


1

Waves are shaken on a rope by moving point P up and down.

Crests are generated when the displacement of P is positive, and troughs are made by negative displacements of P.

Label the crests and troughs on the diagram.



4

Newton's third law applies to this case, therefore we can say that the change of momentum of the wall must be

______ _______.
(units)

Hint: The law of conservation of momentum states that momentum lost by one object in a collision is equal in magnitude to the momentum gained by the other object.

The sum of the changes of momentum is zero, and we know that the change of momentum of the ball is − 24 kg · m/sec.

A2

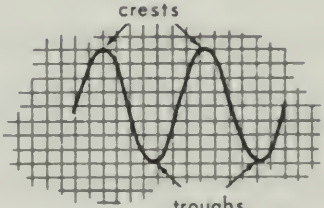
$$v = \frac{\Delta d}{\Delta t}$$

$$\Delta d = 3.0 \text{ m}$$

$$\Delta t = 1.0 \text{ sec.}$$

$$v = \frac{3.0 \text{ m}}{1.0 \text{ sec}} = 3.0 \text{ m/sec}$$

A1



A4

$$\Delta\vec{p}_{wall} + \Delta\vec{p}_{ball} = 0$$

$$\Delta\vec{p}_{wall} = -\Delta p_{ball}$$

$$= -\left(-24 \frac{\text{kg}\cdot\text{m}}{\text{sec}}\right)$$

$$\boxed{\Delta\vec{p}_{wall} = +24 \frac{\text{kg}\cdot\text{m}}{\text{sec}}}$$

3

A brief disturbance that moves through a medium is called a *pulse*.

In the case of the previous two frames, the medium is (i) ______________________ , and the source of the pulse is (ii) ___________________ .

2

A complete waveform is a cycle.

Draw 3 cycles between points P and P'.

5

Now suppose that the wall is hit by a stream of such balls, each of mass 2.0 kg and velocity of +12 m/sec. Suppose that 1000 balls hit the wall head-on during 10 seconds.

The total change of momentum of the wall in that 10-second period is ______ ______.
(units)

— — — — — — — — — — — — — — — — — —

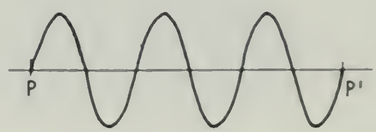
Hint: Calculate the change of momentum for 1000 balls.
Momentum is conserved, therefore the momentum change of the wall is equal to the momentum change of the 1000 balls, but opposite in sign.

A3

(i) the rope

(ii) the hand movement of the 'sender'.

A2



A5

$$\Delta \vec{p}_{wall} = -24 \frac{kg \cdot m}{sec}$$

$$\Delta \vec{p}_{\substack{1000 \\ balls}} = -24000 \frac{kg \cdot m}{sec}$$

$$\Delta \vec{p}_{wall} + \Delta \vec{p}_{\substack{1000 \\ balls}} = 0$$

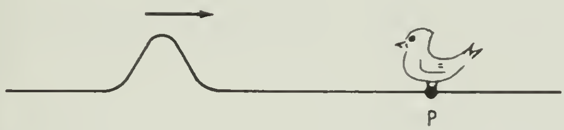
$$\Delta \vec{p}_{wall} = -\Delta \vec{p}_{\substack{1000 \\ balls}}$$

$$= -\left(-24000 \frac{kg \cdot m}{sec} \right)$$

$$\boxed{\Delta \vec{p}_{wall} = +24000 \frac{kg \cdot m}{sec}}$$

4

A small object is fastened to the rope.
Draw the object and pulse when the pulse is centered at point P.

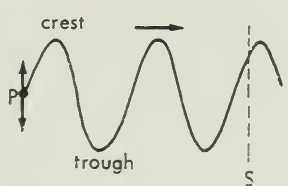


3

In one second, point P makes 6 cycles, and each cycle contains a crest and a trough.

(i) How many cycles per second pass an observer at point S?

(ii) How many troughs pass the observer at S in one second?



Note: Actually, the changes of momentum occur in bumps, one bump when each ball strikes the wall. You can still calculate the total change of momentum, then use this total change to calculate an average force. Just forget that the momenta changes occur in bumps, and divide the total change of momentum by the total time (ten seconds in this case) and obtain average force, $\vec{F}_{av}$.

The following frame is an illustration of this point.

A4

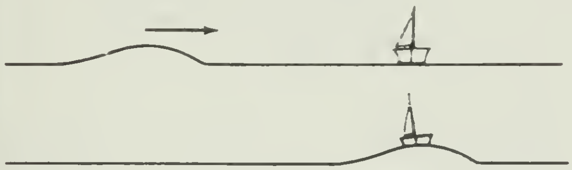
A3

(i) 6 cycles

(ii) 6 troughs

5

We know that the water wave below contains energy because ______________________.



4

The number of cycles per second is the frequency of the wave. (In the last question, the frequency was 6 cycles per second.)

If 12 cycles are produced in 3.0 seconds, the frequency of the waves is ________ ________ (units).

6

The average force on the wall, during the ten second period, due to all 1000 balls losing momentum, is given by applying Newton's second law to the whole collection of balls.

$$\vec{F} = m\vec{a} \qquad \text{and} \qquad a = \frac{\Delta \vec{v}}{\Delta t}.$$

Hence

$$\vec{F} = m\frac{\Delta \vec{v}}{\Delta t} = \frac{m\Delta \vec{v}}{\Delta t} = \frac{\Delta (m\vec{v})}{\Delta t} = \frac{\Delta \vec{p}}{\Delta t}.$$

Average force, $\vec{F}_{av}$, on the wall must be ________ ________ (units).

A5

For one thing, the wave lifts the boat. The increase in the boats gravitational potential energy must have come from the wave.

A4

$$f = \frac{12 \text{ cycles}}{3.0 \text{ sec}} = 4.0 \text{ cycles/sec}$$

A6

$$\vec{F}_{wall} = \frac{\Delta \vec{p}_{wall}}{\Delta t}$$

$$\Delta \vec{p}_{wall} = +24000 \frac{\text{kg} \cdot \text{m}}{\text{sec}}$$

$$\Delta t = 10 \text{ sec}$$

$$\vec{F}_{wall} = \frac{+24000 \text{ kg} \cdot \text{m/sec}}{10 \text{ sec}}$$

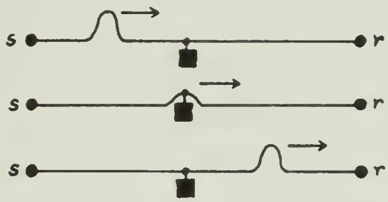
$$= +2400 \frac{\text{kg} \cdot \text{m}}{\text{sec}^2}$$

$$\boxed{\vec{F}_{av} = +2400 \text{ newtons}}$$

6

If you lift a weight against gravity, you do work, and to do work requires energy.

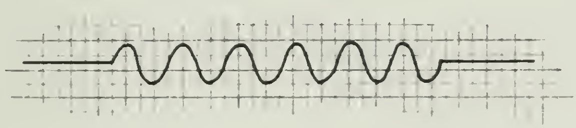
A pulse passes a small weight attached to the rope.



From this experiment it can be seen that the pulse transmits ____________________, because it lifted the weight as it passed.

5

The waves on the diagram were produced in 1.5 seconds.



What is the frequency f in cycles per second?

7

In the previous frames we dealt with inelastic collisions; the balls struck the wall and stopped dead. Suppose 1000 hard steel balls, each of mass 2.0 kg, hit a massive wall head-on in the course of 10 seconds; but this time they arrive with a velocity of +12 m/sec, bounce straight back with equal speed, 12 m/sec, but in the opposite (negative) direction.

The momentum of each ball before impact is

_______ _______.
(units)

A6

energy

A5

$$\frac{6 \text{ cycles}}{1.5 \text{ sec}} = 4.0 \text{ cycles/sec}$$

A7

$$\vec{p} = m\vec{v}$$

$$m = 2.0 \text{ kg}$$

$$\vec{v} = +12 \text{ m/sec}$$

$$\vec{p} = (2.0 \text{ kg})(+12 \text{ m/sec})$$

$$\boxed{\vec{p} = +24 \frac{\text{kg} \cdot \text{m}}{\text{sec}}}$$

Notice that momentum is a vector quantity and the direction of the momentum vector is the direction of the velocity vector.

7

A pulse is a disturbance moving through

(i) ______________________________ , and

transmitting (ii) ______________________ .

6

The quantity T represents the time required to generate one cycle (complete wave). The time interval (T) is called the period of the wave.

When f = 1 cycle/sec; T = 1 sec/cycle

f = 2 cycles/sec; T = 1/2 sec/cycle

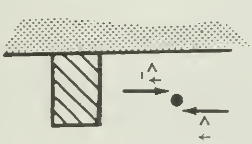
f = 3 cycles/sec; T = 1/3 sec/cycle

In general:

f = x cycles/sec; T = ____________ .

8

The momentum of each ball after impact is ________ ________.
(units)



The diagram shows the direction of the velocity before ($\vec{v}$) and after ($\vec{v}'$) impact.

Hint: This is easy, but watch the sign indicating the direction of the vector.

A7

(i) a medium

(ii) energy

A6

$T = \frac{1}{x}$ sec/cycle.

A8

$\vec{p}' = m\vec{v}'$

$m = 2.0$ kg

$\vec{v}' = -12$ m/sec

$\vec{p}' = (2.0 \text{ kg})(-12 \text{ m/sec})$

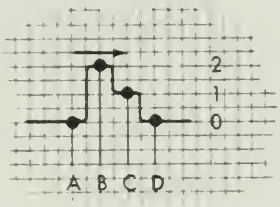
$$\boxed{\vec{p}' = -24 \frac{\text{kg} \cdot \text{m}}{\text{sec}}}$$

The minus sign before the answer means that the momentum of each ball after collision is directed in the opposite direction from the momentum before collision.

8

A disturbance can be described as a displacement of particles in a medium from their normal positions.

Using the information below, complete the table.



Displacement	0			
Point	A	B	C	D

7

From frame 6 we see that the period is related to the frequency of a wave.

$T = \frac{1}{f}$, and $f = \frac{1}{T}$.

What is the period of a wave whose frequency is 10 cycles/sec?

9

The change of momentum of one ball is _______ ________ (units) .

Hint: The answer is not zero.

A8

Displacement	0	2	1	0
Point	A	B	C	D

A7

$$T = \frac{1}{f}$$

$$= \frac{1}{10} \text{ sec/cycle}$$

$$= 0.1 \text{ sec/cycle}$$

A9

$$\Delta\vec{p} = \vec{p}' - \vec{p}$$

$$\vec{p}' = -24 \frac{\text{kg}\cdot\text{m}}{\text{sec}}$$

$$\vec{p} = +24 \frac{\text{kg}\cdot\text{m}}{\text{sec}}$$

$$\Delta\vec{p} = -24 \frac{\text{kg}\cdot\text{m}}{\text{sec}} - \left(+24 \frac{\text{kg}\cdot\text{m}}{\text{sec}}\right)$$

$$\boxed{\Delta\vec{p} = -48 \frac{\text{kg}\cdot\text{m}}{\text{sec}}}$$

9

Draw a possible pulse that has the following displacements:

Displacement	0	-1	0	+2	+2	0	0
At Point	A	B	C	D	E	F	G

8

The frequency of a wave is the number of (i) ______________ that pass a point per (ii) ______________ , and is equal to the inverse of the (iii) ______________.

10

For each collision the change of momentum of the wall is ______ ______ .
(units)

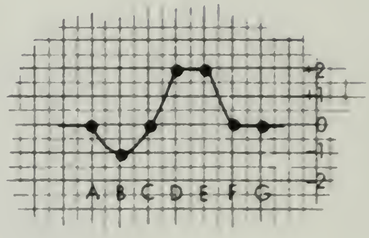
Hint: Momentum is conserved in elastic collisions too.

$\Delta\vec{p}_{wall} + \Delta\vec{p}_{ball} = 0.$

Confused? Return to frame 4 and again follow the argument on this point.

A9

one possibility:



A8

(i) cycles

(ii) second

(iii) period

A10

$$\Delta\vec{p}_{wall} + \Delta\vec{p}_{ball} = 0$$

$$\Delta\vec{p}_{wall} = -\Delta\vec{p}_{ball}$$

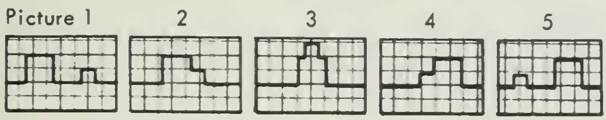
$$\Delta\vec{p}_{ball} = -48\,\frac{kg \cdot m}{sec}$$

$$\Delta\vec{p}_{wall} = -(-48\,\frac{kg \cdot m}{sec})$$

$$\boxed{\Delta\vec{p}_{wall} = +48\,\frac{kg \cdot m}{sec}}$$

10

Two pulses are shaken onto the rope from opposite ends, and the pulses pass at mid-rope. A "movie camera" series shows the interaction of the two pulses.

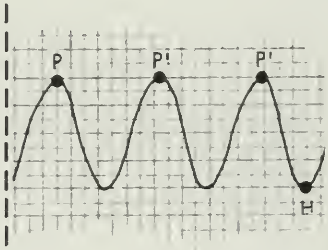


Has there been any change in the shape of the pulses as a result of the interaction?

9

Points marked P' on the diagram correspond to the point P because they are in the same part of a complete cycle.

On the diagram, mark points H' that correspond to the point H.



11

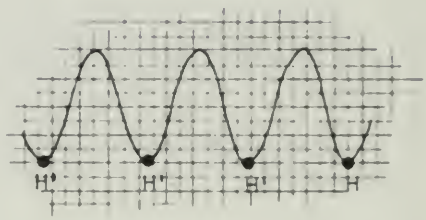
When each ball collides with the wall, the wall undergoes a momentum change of +48 kg · m/sec.

If, during 10 seconds, 1000 balls strike the wall and rebound thus, the total change in momentum of the wall is ______ ______ .
(units)

A10

no

A9



A11

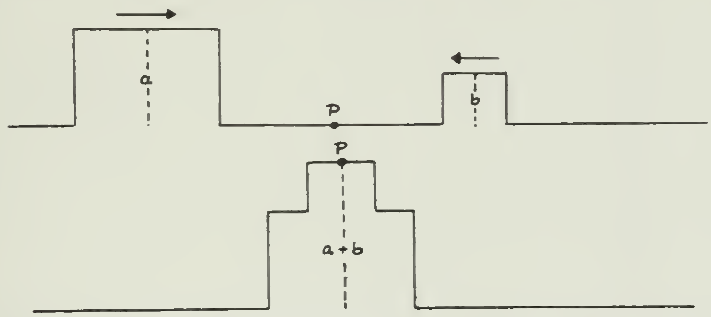
$$\Delta\vec{p}_t = 1000 \cdot \Delta p$$

$$\Delta\vec{p}_t = (1000)\ (+48\ \frac{kg \cdot m}{sec})$$

$$\boxed{\Delta\vec{p}_t = +48000\ \frac{kg \cdot m}{sec}}$$

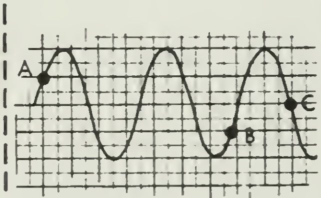
11

When two waves pass through the same region of a medium, the displacement of each point is the sum of the displacements that each wave would cause by itself. For example, as two pulses of displacements a and b pass a point P on a rope, the displacement of point P will be a + b:



10

On the wave diagram, mark as A', B' and C' all points which correspond respectively to points marked A, B and C.



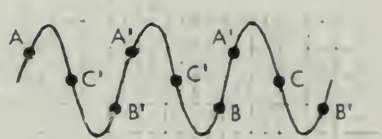
12

Average force on the wall is ______ ______ .
(units)

Hint: Remember the equation from Newton's second law:

$$\vec{F}_{av} = \frac{m\Delta\vec{v}}{\Delta t} = \frac{\Delta(m\vec{v})}{\Delta t} = \frac{\Delta\vec{p}}{\Delta t}.$$

A10



A12

$$\vec{F}_{av} = \frac{\Delta\vec{p}}{\Delta t}$$

$$\Delta\vec{p} = +48000\ \frac{kg \cdot m}{sec}$$

$$\Delta t = 10\ sec$$

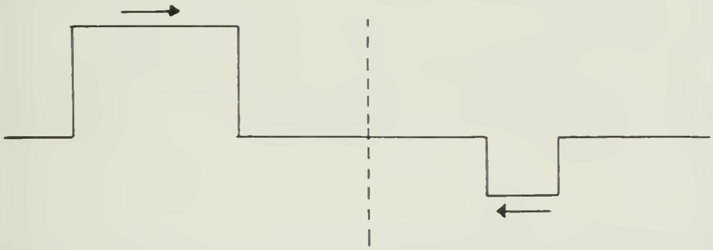
$$\vec{F}_{av} = \frac{+48000\ kg \cdot m/sec}{10\ sec}$$

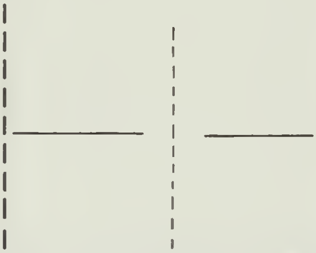
$$\vec{F}_{av} = +4800\ \frac{kg \cdot m}{sec^2}$$

$$\boxed{\vec{F}_{av} = +4800\ \text{newtons}}$$

12

Sketch what the displacement of the rope will be as the two pulses arrive at the center of the rope:



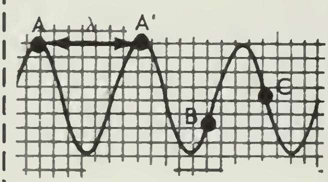


11

The Greek letter lambda (λ) is used to represent wavelength.

The wavelength is the distance between corresponding points of adjacent cycles. For example, points A and A' are one λ apart.

On the diagram mark points whose separation is λ from points B and C.



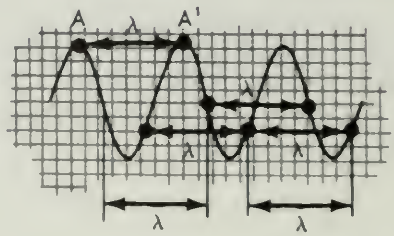
13

The balls are directed at a patch of wall whose dimensions are 2.0 m high by 3.0 m wide.

The area in which the balls impact is ______ ______(units).

A12

A11



A13

area = height × width

height = 2.0 m

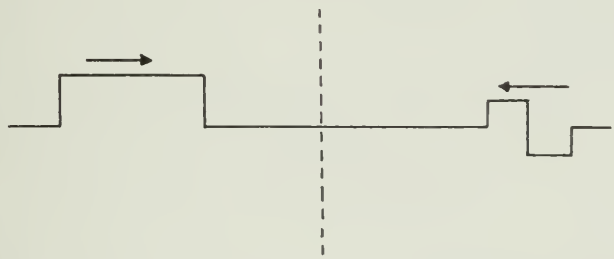
width = 3.0 m

area = (2.0m) (3.0 m)

area = 6.0 m^2

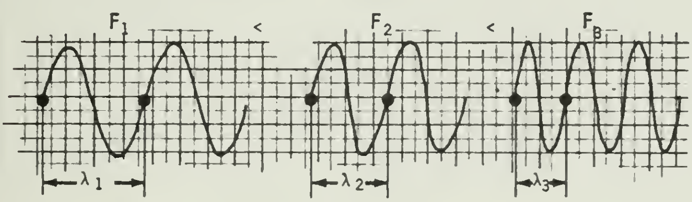
13

Sketch what the displacement of the rope will be as the two pulses arrive at the center of the rope.



12

Higher frequencies in the same medium produce shorter wavelengths.



Mathematically speaking, the wavelength are frequency are ______________ proportional.

14

Pressure is usually defined as the ratio of perpendicular force to the area, and written as

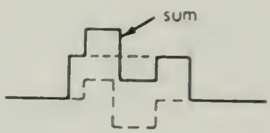
$$\text{pressure} = \frac{\text{force}}{\text{area}} .$$

The pressure on the patch of wall due to the impacting balls is ________ $\underset{\text{(units)}}{\underline{\hspace{2cm}}}$.

— — — — — — — — — — — — — — — — —

Hint: From previous problems, area = 6.0 m² and force (on the wall) = +4800 newtons.

A13



A12

inversely

A14

$$\text{pressure} = \frac{\text{force}}{\text{area}}$$

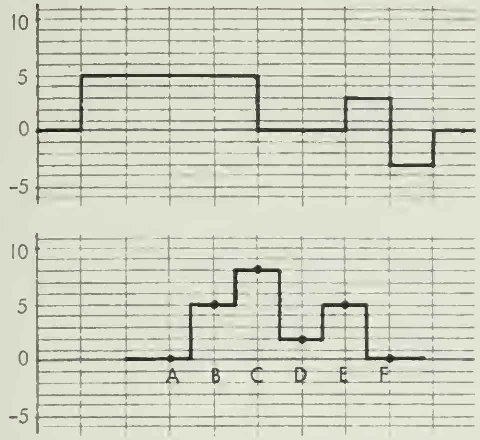
force = +4800 N

area = 6.0 m²

$$\text{pressure} = \frac{+4800\ \text{N}}{6.0\ \text{m}^2}$$

pressure = 800 N/m^2

14

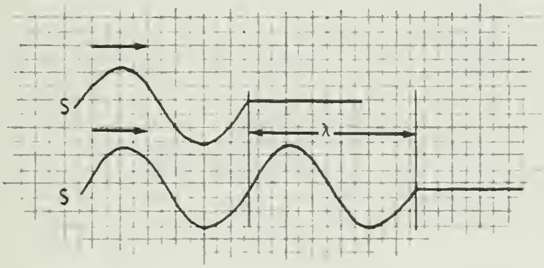


The two pulses in the top diagram are shown superposed in the lower diagram. Complete the displacement table for the labeled points.

Displacement						
Point	A	B	C	D	E	F

13

The top diagram shows a wave moving away from source s, and the bottom diagram shows the wave one complete cycle later.

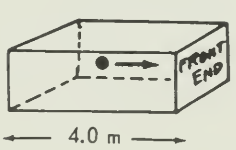


During the time interval from one diagram to the other, the elapsed time is equal to the (i) _______ of the wave, and the wave had moved a distance of (ii) ________ .

(i)

(ii)

Before we make the change from bouncing balls to bouncing molecules, we must look at the behavior of things moving inside a closed box. Suppose we have an oblong box, 4.0 meters long from end to end, with only one ball in it. The ball moves from end to end with a speed of 12 m/sec. The ball hits head-on and rebounds elastically with a speed of 12 m/sec toward the other end. The same ball will hit the front end of the box many times in 10 seconds. Instead of using the number of balls hitting the end, we must calculate and use the number of hits made by this one ball. To find the force on one end, we use the hits on that end only.



A14

Displacement	0	5	8	2	5	0
Point	A	B	C	D	E	F

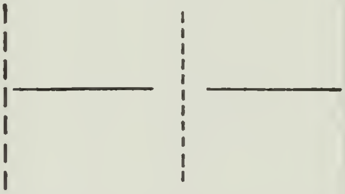
A13

(i) period (T)

(ii) one wavelength (λ)

15

Complete the drawings, showing superposition of the two pulses when the pulse centers coincide.



14

If a wave moves one wavelength λ in one period of time T, wave speed can be calculated.

$$v \text{ (wave speed)} = \frac{\text{distance}}{\text{time}} = \frac{\lambda}{T}$$

Find the speed of a wave whose wavelength λ is 1.5 cm, and whose period T is 0.1 seconds.

15

Between successive hits on the front end of the box, the ball travels one "round trip." It travels the whole length of the box from the front end to the opposite end and back to the front end again.

The distance traveled by the ball during one round-trip is _______________ meters.

A15

At the exact moment they cross the center the displacement is zero.

A14

$$v = \frac{\lambda}{T}$$

$\lambda = 1.5\ \text{cm}$

$T = 0.1\ \text{sec}$

$$v = \frac{1.5\ \text{cm}}{0.1\ \text{sec}}$$

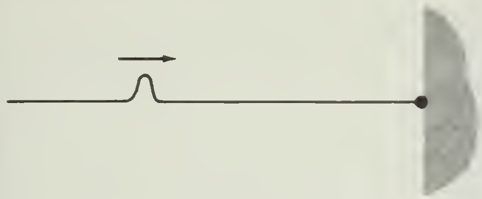
$$= 15\ \text{cm/sec}$$

A15

8.0 meters

16

A pulse on a rope approaches a point that is attached to a wall.



Experiments show that the wave does not continue past the fixed point, but is reflected back in the opposite direction, and the pulse appears on the opposite side of the rope.

Draw the pulse after reflection.

15

Recall that $f = \frac{1}{T}$ (frame 7) and $v = \frac{\lambda}{T}$ (frame 14).

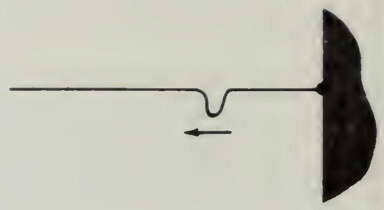
What is the speed of a wave written in terms of wavelength λ and frequency f?

16

The speed of the ball is 12 m/sec. The total distance traveled by the ball in 10 seconds is____________meters.

Hint: Distance is speed times time.

A16



A15

$v = f\lambda$

A16

$d = vt$

$v = 12\ m/sec$

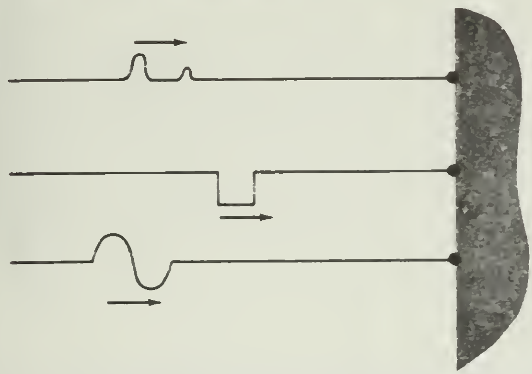
$t = 10\ sec$

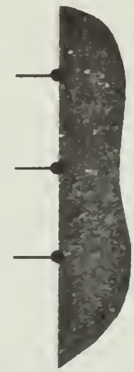
$d = (12\ m/sec)(10\ sec)$

$d = 120\ m$

17

Draw the pulse after reflection.





16

If waves of frequency $f = 20$ cycles per second travel in a particular medium with speed $v = 40$ meters per second,

(i) what is the wavelength of the waves in the medium,

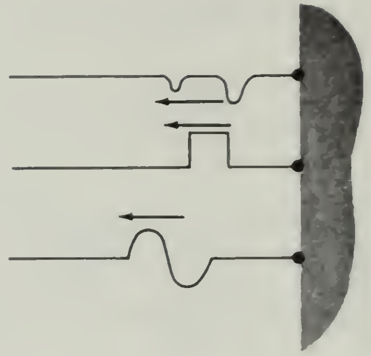
(ii) what is the period of the waves?

17

The number of round trips made by the ball in 10 seconds is ___________.

Hint: From the previous frame, distance traveled in 10 sec is 120 m, and the round trip distance is 8.0 m.

A17



A16

(i) $\lambda = \frac{v}{f}$

$= \frac{40 \text{ m/sec}}{20 \text{ cycles/sec}}$

$= 2.0 \text{ m/cycle}$

Since a cycle is always implied, wavelength is usually written in terms of distance units only. In this example the answer would be reported as $\lambda = 2.0$ m.

(ii) $T = \frac{1}{f} = \frac{1}{20}$

$T = .05$ sec (per cycle)

A17

$\frac{120 \text{ m}}{8.0 \text{ m}} = 15$

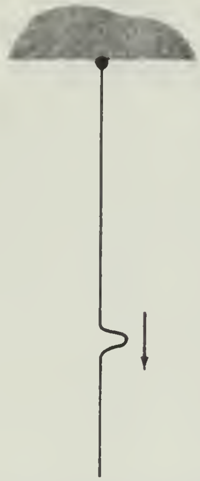
15 round trips

18

A rope is suspended in a stairwell, and a pulse is shaken on the rope from the top.

Experiments show that the wave is reflected from the free end but on the same side of the rope.

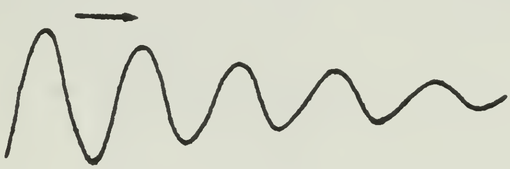
Draw the pulse after reflection.



17

Actually, it is very difficult to produce a perfectly periodic wave. One reason is the dissipation of energy which causes waves to be "damped" or "attenuated."

The figures shows an attenuated (damped) periodic wave.



Of the following, which property is changing?
speed of wave, wavelength, amplitude, frequency, period

18

The number of times that the ball strikes the front end of the box in 10 seconds is ___________ (times).

Hint: The ball strikes the front end of the box once each trip.

A18

A17

On Only *amplitude* is changing. Amplitude refers to the heights of the crests and troughs above and below the undisturbed position. As the figure indicates, the amplitude of the damped wave is decreasing.

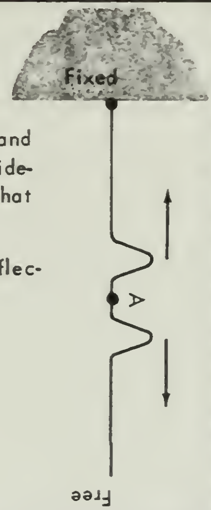
A18

15 times

19

A rope is hung in the diagram, one end fixed and the other end free. At point A the rope is moved sideways and back suddenly, creating similar pulses that travel towards the ends.

Sketch what the pulses will look like after reflection from the ends.



This ends the two programs on waves. To further your knowledge of waves you should refer to some of the other Project Physics materials, especially the Unit 3 laboratory activities, some of the articles in Reader 3 (as for example, "What Is a Wave?" by Albert Einstein and Leopold Infeld), and the following Film Loops:

Superposition
Standing Waves on a String
Standing Waves in a Gas
Vibrations of a Rubber Hose
Vibrations of a Wire
Vibrations of a Drum
Vibrations of a Metal Plate

19

If we want to have 1000 hits on the front wall in 10 seconds, as we had before with the stream of balls, we would have to have more than one ball in the box. In fact, we would need about______ balls, all moving back and forth between the ends.

Hint: Assume that the number of hits is proportional to the number of balls in the box.

Assume that all balls have the same mass and velocity.

A19

A19

$$\frac{1000}{15} = 66.7$$

67 balls

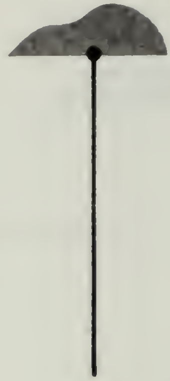
20

What will the rope look like when the two pulses cross?

Pressure is given as force/area; if you know the area of the front of the box you can calculate the average pressure on the end caused by repeated impacts of the balls.

If we have only 67 balls in the box, a calculation of the "pressure" does not seem to be useful. But if the box contains thousands of millions of molecules moving at high speeds, it becomes worthwhile to compute an average result for the invisible particles.

A20



They cancel.

21

After *another* reflection the pulses again cross. What will the rope look like at that instant?

20

So let's now do a similar calculation using gas molecules in a box.

A metal box, 4.0 meters long, with ends 3.0 meters wide by 2.0 meters high, contains one gas molecule which moves to and fro along the length of the box with a speed of 500 meters per second. The molecule bounces elastically from each end, so the speed remains constant at 500 m/sec. The mass of the molecule is approximately 5.0×10^{-26} kilograms.*

The momentum of the molecule before impact with the front end is _______ _______.
(units)

*This is approximately the mass of an average molecule of air.

A21

Both pulses will be on the left side of the rope and so the displacement will be twice that of either pulse alone.

A20

$\vec{p} = m\vec{v}$

$m = 5.0 \times 10^{-26}$ kg

$\vec{v} = 500$ m/sec

$= 5.0 \times 10^{2}$ m/sec

$\vec{p} = (5.0 \times 10^{-26}\,\text{kg})\,(5.0 \times 10^{2}\,\text{m/sec})$

$$\boxed{\vec{p} = +25 \times 10^{-24}\ \frac{\text{kg} \cdot \text{m}}{\text{sec}}}$$

This is the end of Waves 1. Now that you understand the nature of wave pulses, you can study the behavior of trains of wave pulses. This is dealt with in Waves 2 Periodic Waves which begins just below this program in the front of the book.

21

The momentum of the molecule after impact ($\vec{p}'$) with the front end of the box is ______ ______ (units).

A21

$$\vec{p}' = m\vec{v}'$$

$$m = 5.0 \times 10^{-26}\ \text{kg}$$

$$\vec{v}' = -500\ \text{m/sec}$$

$$= -5.0 \times 10^{2}\ \text{m/sec}$$

$$\vec{p}' = (5.0 \times 10^{-26}\ \text{kg})(-5.0 \times 10^{2}\ \text{m/sec})$$

$$\boxed{\vec{p}' = -25 \times 10^{-24}\ \frac{\text{kg}\cdot\text{m}}{\text{sec}}}$$

22

The total change of momentum of the molecule, therefore is ________ ________ (units).

Hint: As before, $\Delta \vec{p} = \vec{p}' - \vec{p}$.

A22

$$\Delta\vec{p} = \vec{p}' - \vec{p}$$

$$\vec{p} = +25 \times 10^{-24}\ \frac{kg \cdot m}{sec}$$

$$\vec{p}' = -25 \times 10^{-24}\ \frac{kg \cdot m}{sec}$$

$$\Delta\vec{p} = (-25 \times 10^{-24}) - (+25 \times 10^{-24})\ \frac{kg \cdot m}{sec}$$

$$\boxed{\Delta\vec{p} = -50 \times 10^{-24}\ \frac{kg \cdot m}{sec}}$$

23

In 10 seconds the molecule can make __________ trips to and fro, and so can make this number of impacts on the front end.

Hint: In 10 seconds the molecule would move 5000 meters, and the round-trip distance is 8.0 meters.

A23

$$\frac{5000\ \text{m}}{8.0\ \text{m per trip}} = \boxed{625\ \text{trips}}$$

24

In 10 seconds, the molecule makes ________ impacts with the front end of the box.

Hint: Read the question in the previous frame.

A24

625 impacts	(one per trip)

25

The change of momentum of the molecule per impact was calculated to be -50×10^{-24} kg · m/sec. Therefore, the total change of momentum of the front wall of the box in 10 seconds is ________ ________ (units).

Hint: The change of momentum of the wall is opposite in direction to the change of momentum of the molecule.

A25

$$\Delta \vec{p}_{wall} = +50 \times 10^{-24} \ \frac{kg \cdot m}{sec} \text{ per impact}$$

$$\Delta \vec{p}_{wall} = (625) \left(+50 \times 10^{-24} \ \frac{kg \cdot m}{sec}\right)$$

$$= +31250 \times 10^{-24} \ \frac{kg \cdot m}{sec}$$

$$\boxed{\Delta \vec{p}_{wall} = +3.12 \times 10^{-20} \ \frac{kg \cdot m}{sec}}$$

26

The average force on the front of the box, during the 10 second period, is ________ ________ (units).

Hint: Remember that the average force was calculated as the change in momentum divided by the time interval.

Still having trouble? Go back to frame 6 and after re-viewing it, give this another try.

A26

$$\overleftarrow{F} = \frac{\Delta(m\overleftarrow{v})}{\Delta t} = \frac{\Delta\overleftarrow{p}}{\Delta t}$$

$$\Delta\overleftarrow{p}_{wall} = +3.12 \times 10^{-20}\ \frac{kg \cdot m}{sec}$$

$$\Delta t = 10\ sec$$

$$\overleftarrow{F} = \frac{+3.12 \times 10^{-20}}{10}\ newtons$$

$$\boxed{\overleftarrow{F} = +3.12 \times 10^{-21}\ newtons}$$

27

The front end wall has dimensions of 2.0 meters by 3.0 meters. The average pressure on the end wall is ________ ________ (units).

Hint: Pressure is force per unit area.

If we were able to make a box with just one molecule in it, we would be quite proud of the vacuum that we had created. Don't expect this pressure to be large.

A27

pressure = force/area

$$\text{area} = 6.0\ \text{m}^2$$

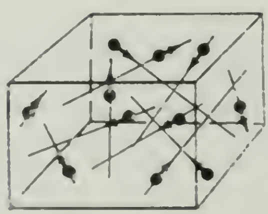
$$\text{force} = 3.12 \times 10^{-21}\ \text{N}$$

$$\text{pressure} = \frac{3.12 \times 10^{-21}\ \text{N}}{6.0\ \text{m}^2}$$

$$\boxed{\text{pressure} = 5.0 \times 10^{-22}\ \text{N/m}^2}$$

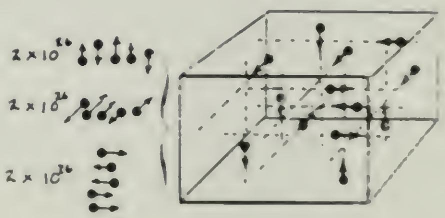
Now suppose that this box contains 6.0×10^{26} molecules (that is, 600,000,000,000,000,000, 000,000,000 molecules). This figure is roughly the number of molecules in such a box if it were filled with air at atmospheric pressure. In reality these molecules would be moving about in all directions at random; but in order to simplify the calculation, suppose that they are sorted out into three groups. One lot moves up and down, another lot moves to and fro along the length, and the third lot moves back and forth across the width. Symmetry considerations suggest we should have the molecules equally divided between the three groups.

(If you wish a more rigorous explanation, think of dividing the velocity of each molecule into three components $\vec{v}_x$, $\vec{v}_y$ and $\vec{v}_z$. This cannot be done individually for each molecule, so it is done statistically for the sample of randomly-moving molecules. The results are the same as given in the first paragraph.)



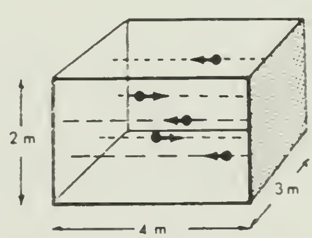
There are 6.0×10^{26} molecules in the box moving in random directions.

Suppose we have three groups, 2.0×10^{26} in each, having some average velocity parallel to one edge of the box.



The pressure on an end of the box will be due only to impacts of molecules moving to and fro along the length. We will now calculate the pressure on the end of the box. The pressure is caused by 2.0×10^{26} molecules, moving at a speed of 500 m/sec, and colliding elastically with the front end of the box.

Assume that the pressure on the end face is due to the impacts of the molecules that are moving parallel to the length of the box.



28

The average pressure on the end of the box will be ________ ________ .
(units)

Hint: Recall from frame 27 that the average pressure due to one molecule was 5.0×10^{-22} N/m^2

In this case we have 2.0×10^{26} molecules colliding with the end of the box.

A28

$$(5.0 \times 10^{-22}\ \text{N/m}^2)(2.0 \times 10^{26}) = 10 \times 10^4\ \text{N/m}^2$$

pressure = 1.0×10^5 N/m^2

The values used for the mass of a molecule and the number of molecules in a box of that size are roughly correct for ordinary air in a room.

Standard atmospheric pressure is 1.0132×10^5 N/m^2.

Thus your calculated result approximates the standard atmospheric pressure quite closely.

29

Suppose that we reduce the size of the box slowly to one-half of the original length (that is, to 2.0 meters). Assume that we do not change the speed of the molecules or the size of the end wall.

The average pressure of the end of the box will now be

________ ________ .
(units)

Hint: This will require that you recalculate the number of hits on the end wall, since the molecules have a shorter distance to travel between impacts.
The rest of the calculations remain as before.

A29

number of impacts per molecule in 10 seconds is 1250

change of momentum per impact is $.50 \times 10^{-24} \frac{kg \cdot m}{sec}$ (per molecule)

2.0×10^{26} molecules strike the face

$$\text{pressure}_{av} = 2.0 \times 10^{5}\ N/m^2$$

This is what you should expect since twice as many impacts per unit of time should result in twice the pressure.

30

If the box is reduced in size to one-half the original length, what effect does this have on the volume of the box?

A30

The volume is reduced to half its original size.

31

How did this change in volume of one-half affect the pressure exerted by the gas?

A31

The pressure of the gos wos doubled.

32

From the calculations made in this program, how is the pressure of a gas related to its volume?

Hint: Assume equal molecular speeds, same number of molecules and perfectly elastic collisions between wall and molecules, and no collisions of molecules.

A32

The pressure of a gas is inversely proportional to the volume it occupies.

Having now completed this program, it should be much easier to follow the more complete discussion of The Kinetic-Molecular Theory of Gases to be found in Chapter 11 of the Project Physics Text, and in other physics books. Also you will now be in a position to enjoy many of the Project Physics Reader 3 articles, such as:

The Great Molecular Theory of Gases by Eric M. Rogers
Entropy and the Second Law of Thermodynamics by Kenneth W. Ford
The Law of Disorder by George Gamow
The Law by Robert M. Coates
The Arrow of Time by Jacob Bronowski

Also in the same Reader, you will find a brief biography of James Clerk Maxwell, the great scientist, who was a key figure in the development of kinetic theory.

0-03-089643-6