

CHAPTER 2

Trigonometry

Scale drawings

Seldom can we directly measure the heights of tall buildings, hills, trees, etc. One way to find the height of a building or tree is to stand away from the object. Now measure the angle between the horizontal and the highest point of the object (using a clinometer, which is just a glorified protractor), then measure the distance between you can the object. By making a scale drawing the height of the object can be readily estimated. See **Figure 1**.

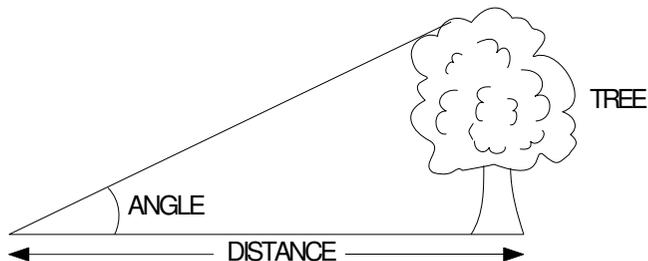


Figure 1.

You couldn't use the same technique to measure the height of a mountain peak which is miles away and covered in clouds. The clouds would get in your way, and you couldn't measure the horizontal distance. An instrument such as a tellinometer would help. This uses radar to locate the top of the mountain. It also measures the angle and distance between you and the top. A scale drawing would provide a way of calculating the height of the mountain. See **Figure 2**.

As a further example suppose we wanted to find the width of a large pond or lake; see **Figure 3**.

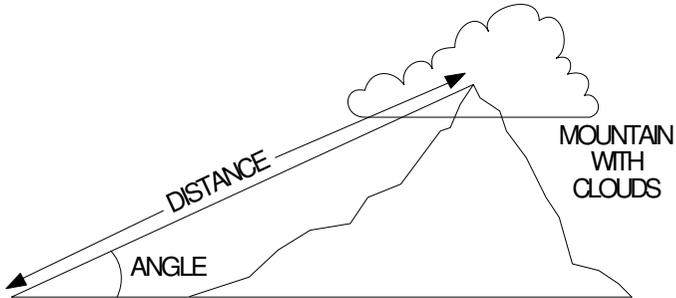


Figure 2.

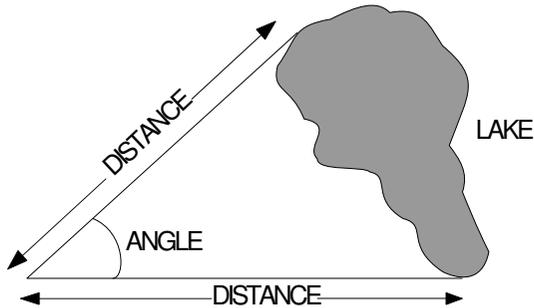


Figure 3.

A scale drawing could be produced from the measurements made, and the required distance estimated.

Here is a related example. A navigator is at a certain position A. He is 150km due west of city B and 188 km from city C. The angle between the two cities is 23 degrees measured from his position. How far apart are the two cities? Again, a scale drawing could provide the answer.

Although scale drawings will provide answers to the problems mentioned above, they are rough and ready. And they cannot always be practicably or accurately reproduced. An alternative approach is to do the necessary calculations by trigonometry using your computer.

The trigonometry functions

The three important trigonometric functions are SIN (sine function), COS (cosine function) and TAN (tangent function). They each represent ratios of the various sides of a right-angled triangle. For example, the triangle shown below is a right-angled triangle. The angle at the corner of the left is denoted by the symbol X. The three sides of the triangle will be referred to as the side adjacent to X, the side opposite X, and the hypotenuse (the longest side).

$$\text{TAN}(X) = \frac{\text{opposite}}{\text{adjacent}}$$

$$\text{SIN}(X) = \frac{\text{opposite}}{\text{hypotenuse}}$$

$$\text{COS}(X) = \frac{\text{adjacent}}{\text{hypotenuse}}$$

Some useful values to remember are the following:

$\text{SIN}(0) = 0$	$\text{COS}(0) = 1$	$\text{TAN}(0) = 0$
$\text{SIN}(30) = 0.5$	$\text{COS}(30) = \text{SQR}(3)/2$	$\text{TAN}(30) = 1/\text{SQR}(3)$
$\text{SIN}(45) = 1/\text{SQR}(2)$	$\text{COS}(45) = 1/\text{SQR}(2)$	$\text{TAN}(45) = 1$
$\text{SIN}(60) = \text{SQR}(3)/2$	$\text{COS}(60) = 1/2$	$\text{TAN}(60) = \text{SQR}(3)$
$\text{SIN}(90) = 1$	$\text{COS}(90) = 0$	

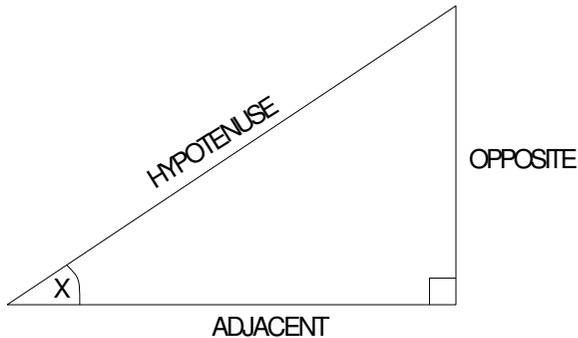


Figure 4.

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If you know the angle X and one of the three lengths of a right-angled triangle then you can find the other two lengths. For example, if you know the angle X and the length of the adjacent side then the other two lengths are given by the following formulae.

$$\begin{aligned}\text{opposite} &= \text{TAN}(X) * \text{adjacent} \\ \text{hypotenuse} &= \text{adjacent} / \text{COS}(X)\end{aligned}$$

Another way of describing the trigonometric function is by using a circle of radius 1 unit. Measure out the angle required as shown in **Figure 5**. The values of the various trigonometric functions are indicated.

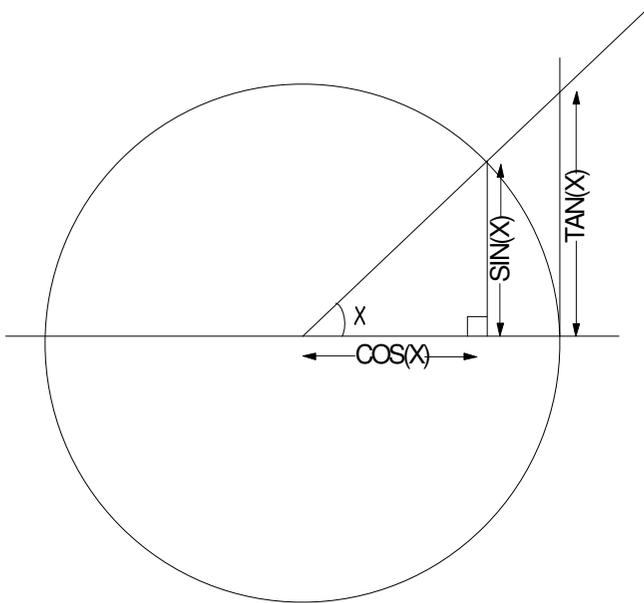


Figure 5.

Mathematically, distances are measured horizontally from left to right and vertically upwards. This explains why, for instance, in Figure 6, $\text{COS}(X)$ has a negative value.

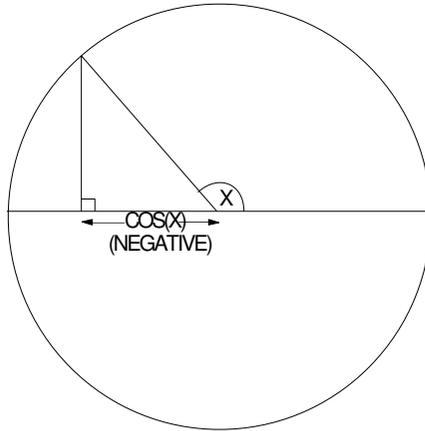


Figure 6.

You can obtain SIN, COS and TAN of an angle X by typing

PRINT SIN(X) etc.,

substituting the appropriate value of X. The only possible problem is that the BBC and Electron micros, in common with most microcomputers, expect the angles in radians, not degrees. Fortunately degrees can be turned into radians and vice versa very easily.

First of all, what is a radian? Draw a circle of radius 1 unit. Measure along the circumference of your circle a distance which is equal to the radius of the circle. The angle subtended by this arc is 1 radian. 1 radian is approximately 57 degrees. See **Figure 7**.

The number PI is both remarkable and famous. It is defined as the ratio of the circumference of a circle to the diameter. The (approximate) value of PI is stored in your micro. Simply type

PRINT PI

to reveal the value stored. In a circle of radius 1 unit the diameter is 2 units. Thus the circumference of the circle is $2 \cdot \text{PI}$ and so there are $2 \cdot \text{PI}$ radians in a complete circle. Since there are 360 degrees in a complete circle we see that

360 degrees = $2 \cdot \text{PI}$ radians, and
180 degrees = PI radians

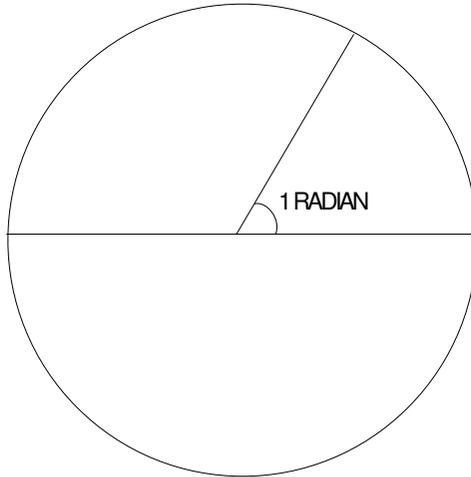


Figure 7.

We can convert degrees to radians and vice versa quite easily with the following formulae:

$$X \text{ degrees} = X * \text{PI} / 180 \text{ radians}$$

$$Y \text{ radians} = Y * 180 / \text{PI} \text{ degrees}$$

More easily, we can use two of the functions available on your computer, RAD and DEG:

$$X \text{ degrees is } \text{RAD}(X) \text{ radians}$$

$$Y \text{ radians is } \text{DEG}(Y) \text{ degrees}$$

The following program can be used to find lengths of right angled triangles. You need to input an angle and one distance. The program calculates the other two lengths.

Listing 2.1

LIST

```
10 REM Program for right-angled triangles
20 CLS:PRINT ' TAB(9);"Right-angled triangles"'
30 PRINT "This program enables you to
```

```

find the"
  40 PRINT "sides of a right angled tri
angle"
  50 PRINT "provided you know one side
and angle."'
  60 PRINT "
                                *
                                **"
  70 PRINT "
                                * *
                                * *"
  80 PRINT "      Hypotenuse * * Oppos
ite
                                * *
  90 PRINT "
                                *Angle *
                                *****"
  95 PRINT "      Adjacent"'
  100 REM Input details
  105 @%=&02040A
  110 REPEAT
  120 INPUT "Angle, in degrees. ";X
  130 IF X<=0 OR X>=90 THEN PRINT "Error
- not a triangle."'
  140 UNTIL X>0 AND X<90
  150 PRINT "'Which side do you know? 1
(Opposite)"
  160 PRINT "2 (Adjacent) or 3 (Hypotenu
se)."

```

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```
270 PRINT CHR$(7) "That's it - anothe
r go? Y or N ";
280 REPEAT:G$=GET$:UNTIL G$="Y" or G$=
"N"
290 IF G$="Y" THEN RUN ELSE CLS:PRINT
'"Bye for now.":END
300 REM Opposite side known
310 PRINT "Adjacent side:" L/TAN(X)
320 PRINT " Hypotenuse:" L/SIN(X)
330 RETURN
350 REM Adjacent side known
360 PRINT "Opposite side:" TAN(X)*L
370 PRINT " Hypotenuse:" L/COS(X)
380 RETURN
400 REM Hypotenuse known
410 PRINT "Opposite side:" SIN(X)*L
420 PRINT "Adjacent side:" L*COS(X)
430 RETURN
```

RUN

Right-angled triangles

This program enables you to find the sides of a right angled triangle provided you know one side and angle.

```
          *
          **
         * *
        * *
Hypotenuse * * Opposite
          * *
         * *
        *Angle *
*****
Adjacent
```

Angle, in degrees. ?30

Which side do you know? 1 (Opposite)
2 (Adjacent) or 3 (Hypotenuse).
Type 1, 2 or 3 ?1

Type in the length of this side.
Length ?0.5

Adjacent side: 0.8660
Hypotenuse: 1.0000

That's it - another go? Y or N

Inverse functions

Suppose we know the length of the sides of a right-angled triangle, can we determine the various angles? The answer is yes, and we use the inverse trigonometric functions to do this. Given an angle X then $\text{TAN}(X)$ gives us a number, the tangent of the angle X . Conversely, given a number N we could find an angle whose tangent is that number. Such an angle could then be called the inverse tangent of N . It is usually denoted by $\text{ATN}(N)$, the arc tangent of N .

Look at the triangle in **Figure 8**.

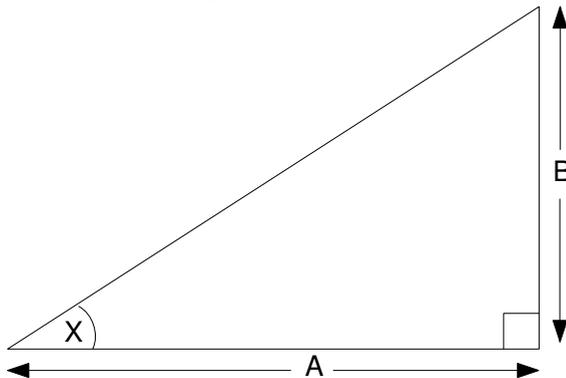


Figure 8.

If we know the values of A and B then we can find the value of the angle X. We know that $\text{TAN}(X) = B/A$, thus $X = \text{ATN}(B/A)$. You can put the appropriate values in this expression and get your computer to print out the answer. Of course, the answer would be in radians. To get an answer in degrees you need to multiply the result by $180/\text{PI}$.

The trigonometric functions SIN and COS also have inverse functions denoted by ASN (arc sine) and ACS (arc cosine) respectively. ASN(N) is that angle whose sine is N; similarly ACS(N) is that angle whose cosine is N. Both of these functions are available on your micro, but it is also interesting to see how easily they can be obtained from the ATN function.

To see how we obtain ASN from ATN look at the right-angled triangle with a hypotenuse of length 1 unit in **Figure 9**.

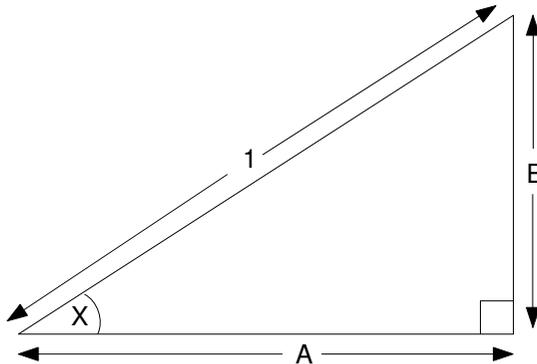


Figure 9.

Now suppose that we know the value of B, and we want to find the angle X. We know that $\text{SIN}(X) = B$ so that $X = \text{ASN}(B)$. If we knew the value of A then we could use ATN since $X = \text{ATN}(B/A)$ also. To find A we use Pythagoras' theorem.

Recall the theorem of Pythagoras. In words, it states that the square of the hypotenuse of a right-angled triangle is equal to the sum of the squares of the other two sides. In symbols we have

$$C^2 = A^2 + B^2$$

where C is the length of the hypotenuse. Since our hypotenuse is of length 1 we have:

$$1 = A^2 + B^2$$

or

$$A^2 = 1 - B^2$$

and so

$$A = \sqrt{1 - B^2}$$

Since $X = \text{ATAN}(B/A)$ we obtain

$$X = \text{ATAN}(B/\sqrt{1 - B^2})$$

also, $\text{ASN}(B) = X$, and so we obtain

$$\text{ASN}(B) = \text{ATAN}(B/\sqrt{1 - B^2})$$

In a similar way we could produce a formula for $\text{ACS}(A)$, such as:

$$\text{ACS}(A) = \pi/2 - \text{ATAN}(A/\sqrt{1 - A^2})$$

You should notice that $\text{ACS}(A) = \pi/2 - \text{ASN}(A)$.

Non right-angled triangles

The first two examples from the scale drawing section may be solved by using the Right-Angled Triangles program. The third example (usually) involves non right-angled triangles.

A triangle has three sides. If we know the values of any three of these (including at least one side) then we can find the values of the other three. For example we might know the length of two sides and one angle. We can then find the length of the third side and the value of the other two angles. To do this we use a formula.

Let's call the three angles in our triangle X, Y and Z; the three sides SX, SY and SZ where side SX is opposite angle X, etc. See **Figure 10**.

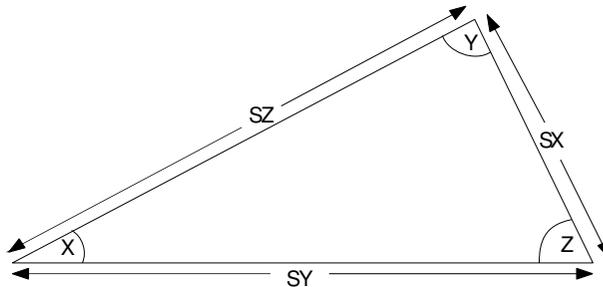


Figure 10.

The following formulae relate the various sides and angles.

The law of cosines

$$SZ^2 = SX^2 + SY^2 - 2 \cdot SX \cdot SY \cdot \cos(Z)$$

$$SY^2 = SX^2 + SZ^2 - 2 \cdot SX \cdot SZ \cdot \cos(Y)$$

$$SX^2 = SY^2 + SZ^2 - 2 \cdot SY \cdot SZ \cdot \cos(X)$$

The law of sines:

$$\sin(X)/SX = \sin(Y)/SY = \sin(Z)/SZ$$

Notice that if Z is a right angle (that is 90 degrees) then $\cos(Z) = 0$ and so the first formula becomes:

$$SZ^2 = SX^2 + SY^2$$

which is just Pythagoras' theorem.

The next program will find the remaining angles and sides provided you know one of the following:

Side Side Side : You know all three sides and are looking for the measurements of the three angles.

Side Side Angle : You know two sides and an angle which is not between them (a non-inclusive angle) and you are looking for the other side and angles.

Side Angle Side : You know two sides and the angle between them (the inclusive angle) and you are looking for the other side and angles.

Side Angle Angle : You know two angles and a side which is not between them (a non-inclusive angle) and you are looking for the other two sides and the third angle.

Angle Side Angle : You know two angles and the side between them (the inclusive side) and you are looking for the other two sides and the third angle.

Notice that in the second case (Side Side Angle) two different triangles are (usually) possible depending on whether the angle opposite side 3 is greater or less than 90 degrees. See **Figure 11** which illustrates this point.

Listing 2.2

LIST

```
10 REM Triangles
20 MODE 1:COLOUR 3:PRINT ' TAB(15);"T
riangles"'
30 PRINT "This program will find the
```

```
remaining"
  40 PRINT "sides and angles of a trian
gle."
  50 PRINT "Which information do you ha
ve?"
  60 PRINT "1> SSS : all 3 sides"
  70 PRINT "2> SSA : 2 sides and non-in
clusive angle"
  80 PRINT "3> SAS : 2 sides and inclus
ive angle"
  90 PRINT "4> SAA : 2 angles and non-i
nclusive side"
  100 PRINT "5> ASA : 2 angles and inclu
sive side"
  110 REM Make selection
  120 REPEAT
  130 INPUT "Type in number ";N
  140 IF N<1 OR N>5 OR N<>INT(N) PRINT
"Try 1, 2, 3, 4 or 5."
  150 UNTIL N>0 AND N<6 AND N=INT(N)
  160 PRINT:ON N GOSUB 210,410,610,810,9
10
  170 COLOUR 3:PRINT ' CHR$(7) TAB(10);"
Another go? Y or N ";
  180 REPEAT:G$=GET$:UNTIL G$="Y" OR G$=
"N"
  190 IF G$="Y" THEN RUN ELSE CLS:PRINT
'"Bye for now.":END
  200 REM All 3 sides
  210 PRINT "*** All 3 sides known"
  220 M=1: SX=FNside(S)
  230 M=2: SY=FNside(S)
  240 M=3: SZ=FNside(S)
  250 A=FNlaw(SY, SZ, SX)
  260 IF ABS(A)>=1 THEN PRINT "Not a tri
angle!":RETURN
  270 PRINT "Angle opposite side 1 is ";
DEG(ACS(A))
```

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```
280 A=FNlaw(SX,SZ,SY)
290 PRINT "Angle opposite side 2 is "
;DEG(ACS(A))
300 A=FNlaw(SX,SY,SZ)
310 PRINT "Angle opposite side 3 is "
;DEG(ACS(A))
320 RETURN
400 REM 2 sides and a non-inclusive an
gle
410 PRINT "*** 2 sides and a non-inclus
ive angle ** "
420 PRINT "Type in the side for which
the opposite angle is known"
430 M=1: SX=FNside(S): AX=FNangle(A)
440 M=2: SY=FNside(S)
450 A=SIN(AX)*SY/SX: IF ABS(A)>1 OR A=0
THEN PRINT "Not a triangle!": RETURN
460 PRINT "Is angle opposite side 2 gr
eater (>) or less (<) then 90 degrees?"
470 REPEAT
480 INPUT "Type > or < "; A$
490 UNTIL A$=">" OR A$="<"
500 AY=DEG(ASN(A)): IF A$=">" AND AY<90
THEN AY=90+AY
510 PRINT "Angle opposite side 2 is "
;AY
520 AZ=PI-AX-AY*PI/180
530 PRINT "Length of side 3 is "; SX*S
IN(AZ)/SIN(AX)
540 PRINT "Angle opposite side 3 is "
;DEG(AZ)
550 RETURN
600 REM 2 sides and the inclusive angl
e
610 PRINT "*** 2 sides and the inclusi
ve angle *** "
620 M=1: SX=FNside(S)
630 M=2: SY=FNside(S)
```

```
640 M=3:AZ=FNangle(A)
650 SZ=SQR(SX*SX+SY*SY-2*SX*SY*COS(AZ)
)
660 IF SZ=0 THEN PRINT "Not a triangle
!":RETURN
670 PRINT "Length of side 3 is ";SZ
680 A=FNlaw(SY,SZ,SX)
690 PRINT "Angle opposite side 1 is "
;DEG(ACS(A))
700 A=FNlaw(SY,SZ,SX)
710 PRINT "Angle opposite side 2 is "
;DEG(ACS(A))
720 RETURN
800 REM 2 angles and a non-inclusive s
ide
810 PRINT "*** 2 angles and a non-inclu
sive side ** "
820 PRINT "Type in the angle for which
the oppositeside is known first.'"
830 M=1:AX=FNangle(A):SX=FNside(S)
840 M=2:AY=FNangle(A)
850 A=PI-AX-AY:IF A<=0 THEN PRINT "Not
a triangle!":RETURN
860 PRINT "Length of side 2 is ";SX*S
IN(AY)/SIN(AX)
870 PRINT "Angle of opposite side 3 i
s ";DEG(A)
880 PRINT "Length of side 3 is ";SX*S
IN(A)/SIN(AX)
890 RETURN
900 REM 2 angles and an inclusive side
910 PRINT "**** 2 angles and an inclusi
ve side *** "
920 M=1:AX=FNangle(A)
930 M=2:AY=FNangle(A)
940 M=3:SZ=FNside(S)
950 A=PI-AX-AY:IF A<=0 THEN PRINT "Not
a triangle!":RETURN
```

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```
960 PRINT "Angle opposite side 3 is ";
DEG(A)
970 PRINT "Length of side 1 is ";SZ*S
IN(AX)/SIN(A)
980 PRINT "Length of side 2 is ";SZ*S
IN(AY)/SIN(A)
990 RETURN
1000 REM get a side
1010 DEF FNside(S)
1020 @%=10:COLOUR 2
1030 REPEAT
1040 S=0:PRINT "Type length of side "
;M;" : ";:INPUT S:PRINT
1050 IF S<=0 THEN PRINT "Not a triang
le!"
1060 UNTIL S>0
1070 @%=&02020A:COLOUR 1
1080 =S
1100 REM get an angle
1110 DEF FNangle(A)
1120 @%=10:COLOUR 2
1130 REPEAT
1140 A=0:PRINT "Type angle opposite s
ide ";M;" : ";:INPUT A:PRINT
1150 IF A<=0.001 OR A>=180 THEN PRINT
"Not a triangle!"
1160 UNTIL A>0.001 AND A<180
1170 @%=&02020A:COLOUR 2
1180 A=RAD(A)
1190 =A
1200 REM Define formula for cosine form
ula
1210 DEF FNlaw(A,B,C)=(A*A+B*B-C*C)/(2*
A*B)
```

RUN

Triangles

This program will find the remaining sides and angles of a triangle.

Which information do you have?

1> SSS : all 3 sides

2> SSA : 2 sides and non-inclusive angle

3> SAS : 2 sides and inclusive angle

4> SAA : 2 angles and non-inclusive side

5> ASA : 2 angles and inclusive side

Type in number ?4

** 2 angles and a non-inclusive side **

Type in the angle for which the opposite side is known first.

Type angle opposite side 1 : ?35

Type length of side 1 : ?2.5

Type angle opposite side 2 : ?55

Length of side 2 is 3.57

Angle of opposite side 3 is 90.00

Length of side 3 is 4.36

Another go? Y or N

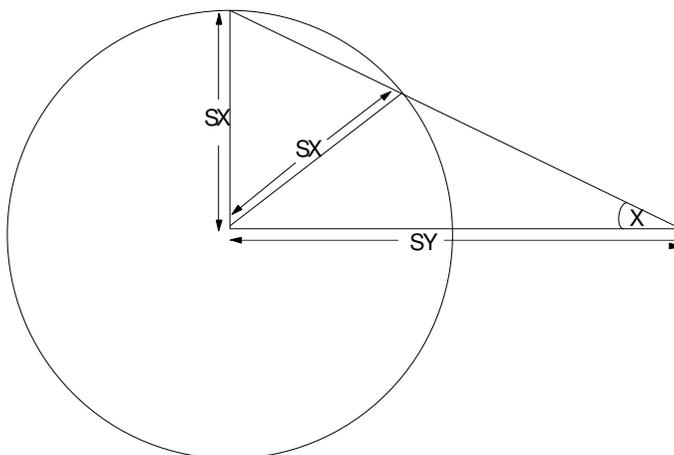


Figure 11.

Refraction

Things often look distorted when viewed through glass or plastic; eg water looks shallower than it actually is. The reason is refraction. When a ray of light travels from one medium (air) to another (glass, water . . .) it is bent or refracted. The angle at which the ray hits the glass is called the angle of incidence; the angle after it has been refracted is called the angle of refraction — see **Figure 12**.

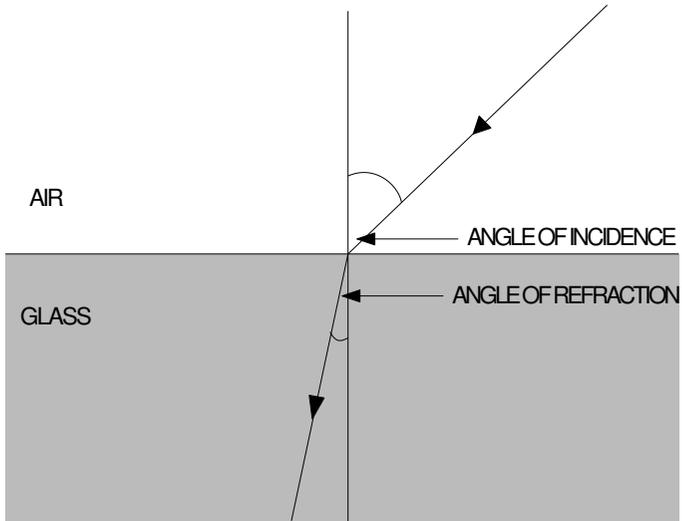
For any given material there is a fixed relation between the angles of incidence and refraction. This is given by Snell' law which states that the ratio of the sine of the angle of incidence to the sine of the angle of refraction is constant for any material (in air). This ratio is called the refractive index.

$$\text{refractive index} = \frac{\text{SIN}(\text{angle of incidence})}{\text{SIN}(\text{angle of refraction})}$$

For glass the refractive index is about 1.5, for water it is 1.333, while for

diamond it is 2.417.

Figure 12.



The program allows you to determine the angle of refraction, assuming that you know the angle of incidence and the refractive index.

Listing 2.3

```
LIST
  10 REM Refraction program
  20 MODE 1:COLOUR 3:PRINT ' TAB(15);"R
efraction"'
  30 PRINT "This program calculates the
angle of"
  40 PRINT "refraction when a ray of li
ght hits"
  50 PRINT "another medium."'
  60 @%=10
 100 REM Input details
```

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```
110 COLOUR 2:PRINT "Type in angle of i
ncidence, in degrees."
120 REPEAT
130 INPUT "Angle: ";X
140 IF X<=0 OR X>=90 THEN COLOUR 3:PR
INT "Error - nonsense":COLOUR 2
150 UNTIL X>0 AND X<90
160 PRINT "What is the refractive ind
ex of the medium?"
170 REPEAT
180 INPUT "Refractive index: ";R
190 IF R<=0 THEN COLOUR 3:PRINT "Funn
y - try again":COLOUR 2
200 UNTIL R>0
210 X=RAD(X)
220 REM Calculate
230 Y=SIN(X)/R:COLOUR 1
240 PRINT "Angle of refraction: ";INT
(DEG(ASN(Y))*100)/100;" degrees."
250 PRINT "Percentage of angle of inc
idence: ";INT(ATN(Y)*100/X);"%"
260 COLOUR 3:PRINT ' CHR$(7) "That's i
t - another go? Y or N ";
270 REPEAT:G$=GET$:UNTIL G$="Y" OR G$=
"N"
280 IF G$="Y" THEN RUN
290 CLS:PRINT "Bye for now.":END
```

RUN

Refraction

This program calculates the angle of refraction when a ray of light hits another medium.

Type in angle of incidence, in degrees.
Angle: ?25

What is the refractive index of the medium?

Refractive index: ?1.333

Angle of refraction: 18.48 degrees.

Percentage of angle of incidence: 70%

That's it - another go? Y or N

Reflection

A piece of glass or the surface of water occasionally behaves like an ordinary mirror, reflecting everything. This occurs when the angle of incidence is too great and the ray of light is reflected. The smallest angle at which this occurs is called the critical angle of the medium. This is given by the following simple formula:

$$\text{SIN}(\text{critical angle}) = \frac{1}{\text{refractive index}}$$

Thus the critical angle can be determined from the refractive index by using the ASN function.

