STEP Support Programme

Assignment 8

Warm-up

1 By considering $(x - y)^2$, prove that $x^2 + y^2 \geqslant 2xy$ and hence show that, if a and b are non-negative numbers, then

$$\frac{a + b}{2} \geqslant \sqrt{ab}. \tag{$*$}$$

What can you say about a and b if $\frac{1}{2}(a + b) = \sqrt{ab}$?

General remark: to show that $A \geqslant B$, it is often easiest to show (equivalently) that $A - B \geqslant 0$.

The inequality $(*)$ is called the AM-GM inequality: AM stands for *Arithmetic Mean* (the left hand side of $(*)$) and GM stands for *Geometric Mean* (the right hand side of $(*)$). Thus the inequality $(*)$ says that for two non-negative numbers, AM is not less than GM. This is an extremely powerful result, which extends — as we shall see below — to more than two numbers.

(i) Prove that $x^2 + y^2 + z^2 \geqslant xy + yz + zx$. What can you say about x, y and z when equality holds in this equation?

You might like to start by multiplying both sides by 2.

(ii) Write out the following, giving careful explanations of each step (a typical explanation might be   ' ... using $(*)$ with $a = p$ and $b = q$'):

$$\frac{p + q + r + s}{4} \geqslant \frac{\sqrt{pq} + \sqrt{rs}}{2} \geqslant \sqrt[4]{pqrs}$$

Hence AM $\geqslant$ GM for four numbers. For this and the next part, you should lay out your work carefully, with a new line for each step. Start by splitting the first fraction into two parts and note that if $A \geqslant C$ **and** $B \geqslant D$ then $A + B \geqslant C + D$.

(iii) Write out the following, giving careful explanations of each step (you will need to use the result of part (ii) above):

$$\frac{p + q + r}{3} = \frac{p + q + r}{4} + \frac{p + q + r}{12} \geqslant \sqrt[4]{pqr \left(\frac{p + q + r}{3} \right)} \, .$$

Deduce that

$$\frac{p + q + r}{3} \geqslant \sqrt[3]{pqr} \, .$$

Hence AM $\geqslant$ GM for three numbers. It seems strange to prove the result for the seemingly more complicated four-number case first, then work back to the three-number case; in fact, this is the basis of the very beautiful method ('backward induction') used by Cauchy to prove the general n-number case. It may be helpful to write $\frac{p+q+r}{3} = z$. Some index manipulation is required at the end.
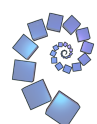
Preparation

2 **(i)** Find the equation of the circle which has the line joining $(1,5)$ to $(-5,13)$ as its diameter.

(ii) Find the (real) solutions of the following simultaneous equations:

(a) $x^2 + y^2 = 25$ and $x^2 + (y-7)^2 = 18$

(b) $x^2 + y^2 = 25$ and $x^2 + (y-7)^2 = 4$

(c) $x^2 + y^2 = 25$ and $x^2 + (y-7)^2 = 1$

In each case, illustrate the result by sketching a diagram.

(iii) For the equations in part **ii(a)** above, show that, if a circle with centre (a,b) passes through the two points of intersection, then $a = 0$. Find the equation of such a circle with centre $(0,2)$.

(iv) Solve the simultaneous equations

$$x^2 + y^2 = 4$$
$$8x^2 + 4(y-1)^2 = 36$$

You may like to sketch these equations using Wolfram Alpha or Desmos to see what is happening.

The STEP question

3 Show that the equation of any circle passing through the points of intersection of the ellipse $(x+2)^2 + 2y^2 = 18$ and the ellipse $9(x-1)^2 + 16y^2 = 25$ can be written in the form

$$x^2 - 2ax + y^2 = 5 - 4a \ .$$

Don't be put off by the word 'ellipse' in the question: you don't have to know anything at all about ellipses to do the question. You need to find the points of intersection between two curves, so start by doing this.

Similarly if a question uses the term "hyperbola" you can probably still do the question even if you do not know what a hyperbola is.

Also, don't be put off by the rather large coefficients in the quadratic equation you get when finding the points of intersection of the two ellipses: you can — and should — solve the equations without resorting to calculators or internet quadratic equation solvers.

Warm down

4   I have a drawer full of identical red socks, identical blue socks and identical green socks.

    (i)   How many socks must I take to ensure that I have a matching pair?

    (ii)   How many socks must I take to ensure that I have two pairs?

    (iii)   How many socks must I take to ensure that I have n matching pairs?

       There are many ways of tackling this. One approach is to consider picking $2n$ socks, made up of r red socks, b blue socks and g green socks, and decide whether this is enough, in the cases that arise according to whether r, b and g are odd or even and, if it is not enough, determine how many more are required.

       Another approach is to put each sock you pick into either a red bin, a blue bin or a green bin, emptying each bin as soon as it has a pair of socks in it. $2n$ socks might not be enough as you might only have $n - 1$ pairs and (say) one green and one red sock left in the bins. (Why could you not have a spare sock in each of the three bins?) Then consider what could happen as you pull out another sock.

       However you tackle it, you should explain your answer carefully. **Extrapolation from the previous two parts provides guidance and insight, but is not sufficient as a proof.** The point of this question is how well you explain your method: no one really cares what the answer is — after all, you could just look in the drawer and pick a pair.