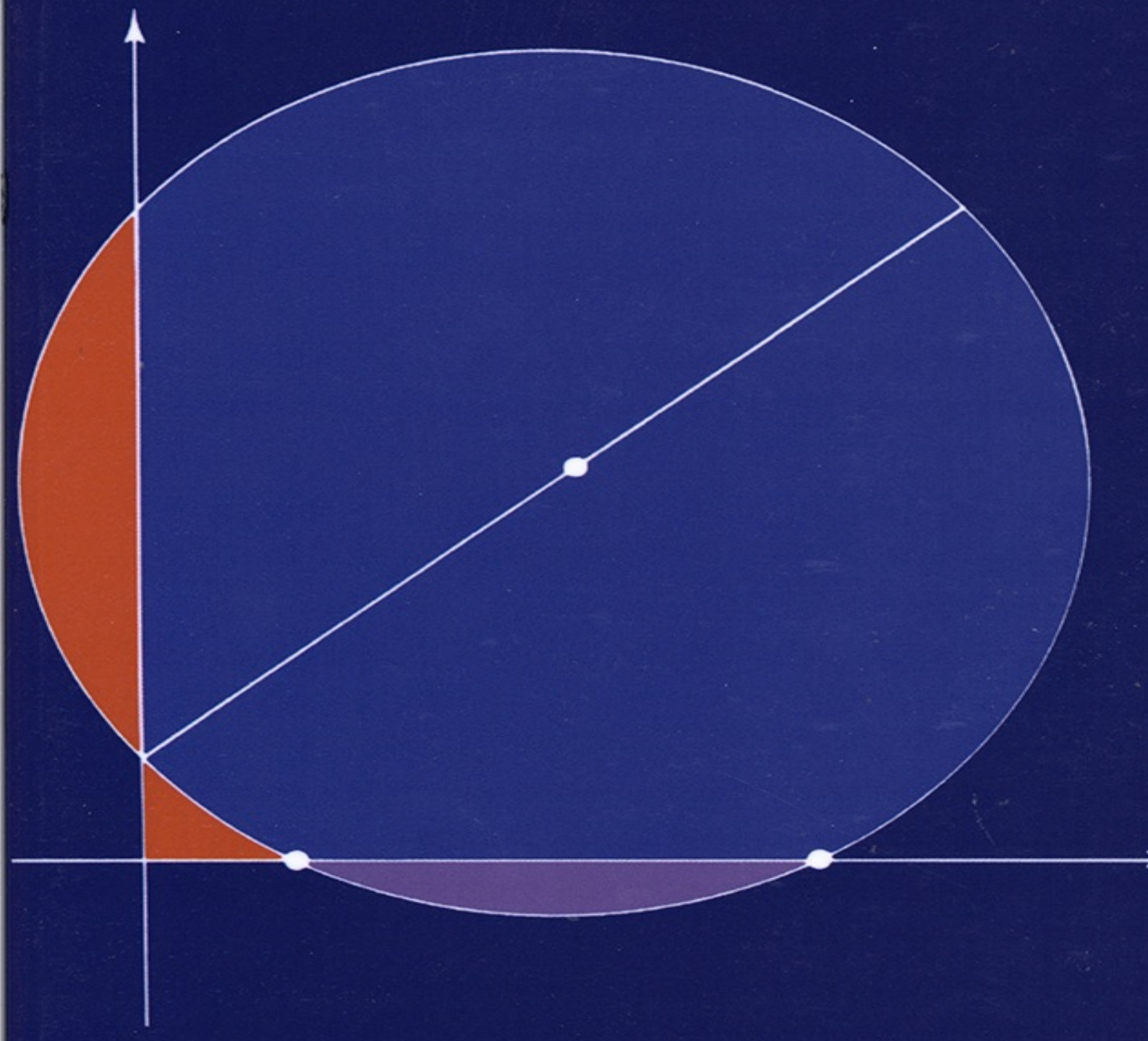


Benjamin Bold

Famous Problems of
GEOMETRY
and How to Solve Them



**Famous Problems
of Geometry
and How to Solve Them**

BENJAMIN BOLD

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To My Wife, CLAIRE,

*Whose Assistance and Encouragement
Made this Book Possible*

Contents

Foreword

I Achievement of the Ancient Greeks

II An Analytic Criterion for Constructibility

III Complex Numbers

IV The Delian Problem

V The Problem of Trisecting an Angle

VI The Problem of Squaring the Circle

VII The Problem of Constructing Regular Polygons

VIII Concluding Remarks

Suggestions for Further Reading

Solutions to the Problems

Foreword

IN JUNE OF 1963 a symposium on Mathematics and the Social Sciences was sponsored by the American Academy of Political and Social Sciences. One of the contributions was by Oscar Morgenstern, who, together with John Von Neumann, had written the book “The Theory of Games and Economic Behavior.” This book stimulated the application of mathematics to the solution of problems in economics, and led to the development of the mathematical “Theory of Games.” Dr. Morgenstern’s contribution to the Symposium was called the “Limits of the Uses of Mathematics in Economics.” I shall quote the first paragraph of this article.

Although some of the profoundest insights the human mind has achieved are best stated in negative form, it is exceedingly dangerous to discuss limits in a categorical manner. Such insights are that there can be no perpetuum mobile, that the speed of light cannot be exceeded, that the circle cannot be squared using ruler and compasses only, that similarly an angle cannot be trisected, and so on. Each one of these statements is the culmination of great intellectual effort. All are based on centuries of work and either on massive empirical evidence or on the development of new mathematics or both. Though stated negatively, these and other discoveries are positive achievements and great contributions to human knowledge. All involve mathematical reasoning; some are, indeed, in the field of pure mathematics, which abounds in statements of prohibitions and impossibilities.”

The above quotation states clearly and forcefully the purpose of this book. Why does mathematics abound in “statements of prohibitions and impossibilities?” Why are the solutions of such problems “squaring the circle” and “trisecting an angle” considered to be “profound insights” and “great contributions to human knowledge?” Why were centuries of “great intellectual effort” required to solve such seemingly simple problems? And, finally, what new mathematics had to be developed to resolve these problems? I hope you will find the answers to these questions as you read this book.

The outstanding achievement of the Greek mathematicians was the development of a postulational system. Despite the flaws and defects of euclidean geometry as conceived by the ancient Greeks, the work serves as a model that is followed even up to the present day.

In a postulational system one starts with a set of unproved statements (postulates) and deduces (by means of logic) other statements (theorems). Two of the postulates of euclidean plane geometry are:

- 1) given any two distinct points, there exists a unique line through the two points.
- 2) given a point and a length, a circle can be constructed with the given point as center and the given length as radius.

These two postulates form the basis for euclidean constructions (constructions using only a unmarked straight edge and compasses). With these two instruments the Greek mathematicians were able to perform many constructions; but they also were unsuccessful in many instances. Thus, they were able to bisect any given angle, but were unable to trisect a general angle. They were able to construct a square equal in area to twice a given square, but were unable to “duplicate a cube.” They were able to construct a square equal in area to a given polygon, but were unable to “square a circle.” They were able to construct regular polygons of 3, 4, 5, 6, 8 and 10 sides, but were unable to construct regular polygons of 7 or 9 sides. Before the end of the 19th century, mathematicians had supplied answers to all of these problems of antiquity. The purpose of this book is to show how these problems were eventually solved.

Why were the Greek mathematicians unable to solve these problems? Why was there a lapse

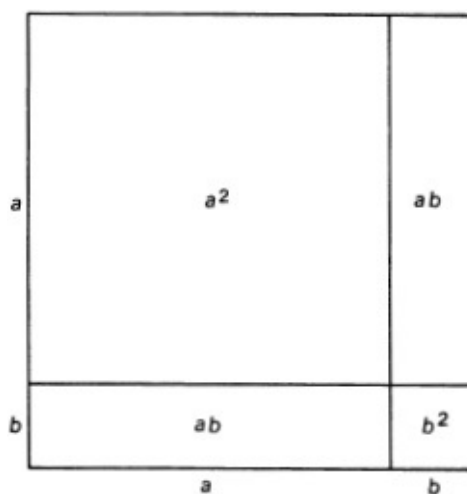
about two thousand years before solutions to these problems were found?

The mathematical efforts of the Greeks were along geometric lines. The concentration on geometry and the resulting neglect of algebra, was due to the following situation:

The Pythagorean theorem tells us that, if the length of a side of a square is one unit, the length of the diagonal is $\sqrt{2}$ units. What kind of number is $\sqrt{2}$? The Greek mathematicians, up to this point, were able to express all their results in terms of integers. Fractions, or rational numbers, are ordered pairs of integers—i.e., numbers of the form a/b , where a and b are integers, $b \neq 0$. No matter how they tried, the Greeks were unable to express $\sqrt{2}$ in terms of integers. As you already know, it can be proven that $\sqrt{2}$ is irrational, and it was not until the 19th century that a satisfactory theory of irrationals was developed.

Because of the lack of such a theory, the course of Greek mathematics took a geometric turn. Thus, when the Greeks wished to expand $(a + b)^2$, they proceeded geometrically as follows:

$$(a + b)^2 = a^2 + 2ab + b^2$$



As we shall show later the solution of the construction problems involves well developed algebraic techniques, and in fact, it was not until algebra and analytic geometry were developed in the 17th century by Vieta, Descartes, Fermat, and others, that procedures were obtained that could be used in a successful attack on the construction problems.

Famous Problems

of Geometry

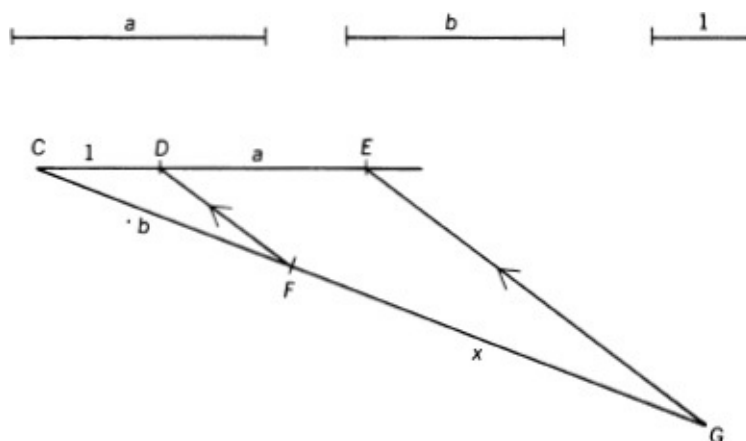
and How to Solve Them

Achievement of the Ancient Greeks

USING GEOMETRIC THEOREMS, the Greek mathematicians were able to construct any desired geometric element that could be derived by a finite number of rational operations and extractions of real square roots from the given elements. To illustrate: Suppose we are given the elements a , b , and the unit element. The Greeks could construct $a + b$, $a - b$, $a \cdot b$, a/b , a^2 , and \sqrt{a} .

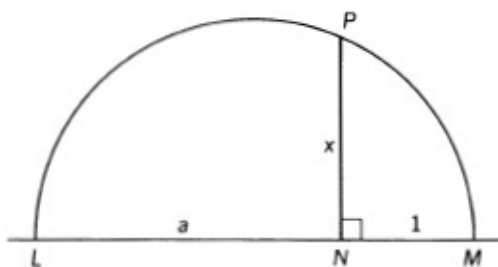
PROBLEM SET I–A

Construct $a + b$ and $a - b$, using the given line segments. The following diagram shows how to construct ab . If EG is constructed parallel to DF , then $x = ab$.



PROBLEM SET I–B

1. Prove that $x = ab$.
2. Using a similar procedure construct a^2 ; a/b ; a^2/b . The diagram below shows how to construct \sqrt{a} .



A semicircle is constructed on LM as a diameter. NP is perpendicular to LM (P is the intersection of the perpendicular and the semicircle). Then $x = \sqrt{a}$.

PROBLEM SET I-C

1. Using the diagram above, prove $x = \sqrt{a}$.
2. Using a similar procedure construct

$$\sqrt{ab}; \sqrt[4]{a}; \sqrt[8]{a}$$

3. Using the Pythagorean theorem construct line segments equal to

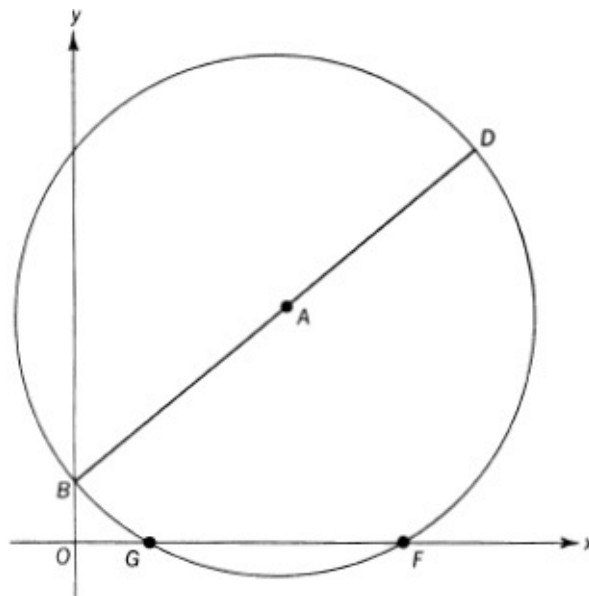
$$\sqrt{2}; \sqrt{3}; \sqrt{5}; \sqrt{17}$$

Using these constructions, the Greeks were able to construct the roots of a linear or quadratic equation if the numbers representing the coefficients were the lengths of given line segments.

PROBLEM SET I-D

Construct the root of $ax + b = c$, where a, b, c are given line segments.

To construct the roots of the quadratic equation $x^2 - ax + b = 0$ ($a^2 > 4b$), one can proceed as follows: Construct a circle whose diameter BD joins the points B(0, 1) and D(a, b). Then the abscissas of G and F (the points where the circle intersects the X-axis) will be the roots of the quadratic equation.



PROBLEM SET I-E

1. Why do we use the restriction $a^2 > 4b$?
2. Prove that the abscissas of G and F are the roots of $x^2 - ax + b = 0$. Hint: Show that the equation of the circle is

$$\left(x - \frac{a}{2}\right)^2 + \left(y - \frac{b+1}{2}\right)^2 = \frac{a^2}{4} + \frac{(b-1)^2}{4}$$

As pointed out in the Introduction, the Greeks (using the basic constructions outlined in the section) achieved considerable success in construction problems. Yet they left a number of unsolved problems for future generations of mathematicians to struggle with. The remainder of this book will be devoted to a brief history of attempts to solve these problems and their final solution in the nineteenth century.

PROBLEM SET I–F

Construct the positive root of $x^2 + x - 1 = 0$, given a unit length.

An Analytic Criterion for Constructibility

TO ANSWER THE QUESTION “Which constructions are possible with unmarked straight edge and compasses?” it is necessary to establish an analytic criterion for constructibility. Every construction problem presents certain given elements $a, b, c \dots$ and requires us to find certain other elements $x, y, z \dots$. The conditions of the problem enable us to set up one or more equations whose coefficients will be numbers representing the given elements $a, b, c \dots$. The solutions of the equations will permit us to express the unknown elements in terms of the given elements. To take a simple example, suppose we wish to construct a square equal in area to twice a given square whose side is a . We express the problem analytically by the equation

$$x^2 = 2a^2$$

Other problems, of course, will lead to equations of higher degree.

We have already seen how the roots of a linear or quadratic equation can be constructed. We shall now investigate the possibility of constructing the roots of an equation of degree greater than 2, and we shall be especially interested in the roots of cubic equations.

First, we know that it is possible to construct any geometric element if that element can be derived from the given elements by a finite number of rational operations (addition, subtraction, multiplication and division), and the extraction of real square roots. Now let us consider the converse situation. If a construction is possible, what is the relation between the required elements and the given elements? It is easy to see that only those constructions are possible for which the number of operations which define the desired elements can be obtained from the given elements by a finite number of rational operations and the extractions of real square roots.

Any construction consists of a sequence of steps, and each step is one of the following:

- 1 drawing a straight line between two points.
- 2 constructing a circle with a given center and given radius.
- 3 finding the points of intersection of two straight lines, two circles, or a straight line and a circle.

Let us assume that we are given a set of coordinate axes and a unit length and that all the given elements can be represented by rational numbers. We know that the sum, difference, product, and quotient (division by 0 is always excluded) of two rational numbers is a rational number. The rational numbers are said to form a closed set with respect to the four fundamental operations. Any set of numbers closed with respect to these four operations is called a field. Let us represent the field of rational numbers by F_0 .

If we are given the coordinates of two points

$$P_1(x_1, y_1) \text{ and } P_2(x_2, y_2)$$

then the equation of the line thru $P_1 P_2$ is

$$(y_2 - y_1)x + (x_1 - x_2)y + (x_2y_1 - x_1y_2) = 0$$

or

$$ax + by + c = 0$$

where

$$a = y_2 - y_1; b = x_1 - x_2; \text{ and } c = x_2y_1 - x_1y_2$$

Note that $x_1, x_2, y_1,$ and y_2 are rational numbers by definition. Then $a, b,$ and c are also rational numbers.

The equation of a circle, whose center is (h, k) and whose radius is $r,$ is

$$x^2 + y^2 - 2hx - 2ky + h^2 + k^2 - r^2 = 0$$

or

$$x^2 + y^2 + dx + ey + f = 0$$

where $d = -2h, e = -2k$ and $f = h^2 + k^2 - r^2.$ Again, $d, e,$ and f are rational numbers. Finding the coordinates of the point of intersection of two straight lines involves only rational operations performed on the coefficients of the variables, whereas finding the coordinates of the intersection of a straight line and a circle, or of two circles, would involve, in addition to the rational operations, on the extraction of square roots. To summarize, we can state that a proposed construction with unmarked straight edge and compasses is possible *if and only if* the numbers which define the desired element can be derived from the given elements by a finite number of rational operations and the extraction of square roots.

PROBLEM SET II–A

Find the coordinates of the points of intersection of

- (a) $ax + by + c = 0$ and $a'x + b'y + c' = 0$
- (b) $ax + by + c = 0$ and $x^2 + y^2 + dx + ey + f = 0$
- (c) $x^2 + y^2 + dx + ey + f = 0$ and

$$x^2 + y^2 + d'x + e'y + f' = 0$$

All rational numbers, i.e., all numbers in $F_0,$ can be constructed if we are given a unit length. Furthermore, if k is a fixed number in F_0 we can construct \sqrt{k} and $a + b\sqrt{k},$ where a and b are any numbers in $F_0.$ If \sqrt{k} is not in $F_0,$ then we can prove that all numbers of the form $a + b\sqrt{k} (a, b, k \in F_0)$ form a new field $F_1,$ which has F_0 as a subfield. For example, let $k = 3,$ then $a + b\sqrt{3}$ form a field F_1 which contains all rational numbers as a subfield, namely all those numbers for which $b = 0.$

To prove that all numbers $a + b\sqrt{k} (a, b, k \in F_0, \sqrt{k}$ not in $F_0)$ form a field we observe that

1. $(a + b\sqrt{k}) + (c + d\sqrt{k}) = (a + c) + (b + d)\sqrt{k}$
 $= e + f\sqrt{k}$
2. $(a + b\sqrt{k}) - (c + d\sqrt{k}) = (a - c) + (b - d)\sqrt{k}$
 $= m + n\sqrt{k}$
3. $(a + b\sqrt{k}) \times (c + d\sqrt{k}) = (ac + bdk) + (ad + bc)\sqrt{k}$
 $= r + s\sqrt{k}$

$$\begin{aligned}
4. \frac{a + b\sqrt{k}}{c + d\sqrt{k}} \cdot \frac{c - d\sqrt{k}}{c - d\sqrt{k}} &= \frac{(ac - bdk) + (bc - ad)\sqrt{k}}{c^2 - d^2k} \\
&= \frac{ac - bdk}{c^2 - d^2k} + \frac{(bc - ad)\sqrt{k}}{c^2 - d^2k} \\
&= u + v\sqrt{k}
\end{aligned}$$

Since a, b, c, d, k are numbers in the field F_0 , the sum, product, difference, and quotient of any two of these rational numbers is a rational number. Therefore e, f, m, n, r, s, u , and v are rational numbers which proves that all numbers of the form $a + b\sqrt{k}$ form a field F_1 , which contains F_0 as a subfield. There is one detail which requires clarification. When $(a + b\sqrt{k})$ was divided by $(c + d\sqrt{k})$ we obtained $u + v\sqrt{k}$

$$u = \frac{ac - bdk}{c^2 - d^2k}$$

and

$$v = \frac{bc - ad}{c^2 - d^2k}$$

Thus u and v are rational numbers if and only if

$$c^2 - d^2k \neq 0$$

We have assumed that \sqrt{k} is not in F_0 . Therefore, $k \neq 0$. Also when we divide we assume the divisor is not 0. Therefore c and d are not both 0, although either c or d may be 0. We now have to show that $c^2 - d^2k \neq 0$. If $c^2 - d^2k = 0$, then $c^2 = d^2k$, $k = c^2/d^2$ and $\sqrt{k} = \pm c/d$. Thus \sqrt{k} would be in F_0 , contrary to the hypothesis. This completes the proof that all numbers of the form $a + b\sqrt{k}$ form a field, F_1 .

Next we can construct all numbers of the form $a_1 + b_1\sqrt{k_1}$ where a_1 and b_1 are any numbers in F_1 , k_1 is a fixed number in F_1 , and the $\sqrt{k_1}$ is not in F_1 . Such a number would be $\sqrt{5} + \sqrt{2}\sqrt[4]{3}$, where $a_1 = \sqrt{5}$, $b_1 = \sqrt{2}$, $k_1 = \sqrt{3}$ are in F_1 and $\sqrt{k_1} = \sqrt[4]{3}$ is not in F_1 . Another example would be $5 + 2\sqrt[4]{3}$. Again we can prove by a process completely analogous to that used above that all numbers of the form $a_1 + b_1\sqrt{k_1}$ form a field F_2 , which has F_1 as a subfield (which contains numbers of the form $a_1 + b_1\sqrt{k_1}$, where $b_1 = 0$).

The process can be continued indefinitely until we reach a field F_n , n , a positive integer. We now have a sequence of fields $F_0, F_1, F_2, \dots, F_n$ with the following properties:

1. F_0 is the field of rational numbers.

F_1 is the field obtained by adjoining \sqrt{k} to F_0 , where k is a fixed number in F_0 such that \sqrt{k} is not in F_0 ; F_1 contains all numbers of the form $a + b\sqrt{k}$, a, b, k in F_0 , \sqrt{k} not in F_0 .

F_2 is the field obtained by adjoining $\sqrt{k_1}$ to F_1 , where k_1 is a fixed number in F_1 such that $\sqrt{k_1}$ is not in F_1 . The field F_2 contains all numbers of the form $a_1 + b_1\sqrt{k_1}$; a_1, b_1, k_1 in F_1 , $\sqrt{k_1}$ not in F_1 .

F_n is the field obtained by adjoining $\sqrt{k_{n-1}}$ to F_{n-1} , where k_{n-1} is a fixed number in F_{n-1} such that $\sqrt{k_{n-1}}$ is not in F_{n-1} . F_n contains all numbers of the form

$$a_{n-1} + b_{n-1}\sqrt{k_{n-1}}; a_{n-1}, b_{n-1}, k_{n-1} \text{ in } F_{n-1}$$

but $\sqrt{k_{n-1}}$ is not in F_{n-1} . A number in F_n may be exceedingly complicated, consisting as it does of several square roots, one over the other. An example of a number in F_4 would be

$$\sqrt{2} - \sqrt{\sqrt{3} + \sqrt{7} + \sqrt{5}}$$

To obtain the number

$$\sqrt{\sqrt{3} + \sqrt{7} + \sqrt{5}}$$

we can start with $k_0 = 5$, then $k_1 = 7 + \sqrt{k_0}$, $k_2 = 3 + \sqrt{k_1}$, $k_3 = \sqrt{k_2}$, and $k_4 = \sqrt{k_3}$. This number is therefore, in F_4 .

2. F_0 is a subfield of F_1 ; F_1 is a subfield of F_2 ; F_{n-1} is a subfield of F_n .

3. Every number in $F_0, F_1, F_2, \dots, F_n$ is constructible, since a number in any one of these fields can be obtained from the unit element by a finite number of rational operations and extractions of square roots.

4. Conversely any constructible number can be found in one of the fields $F_0, F_1, F_2, \dots, F_n$, since we have already shown that only those constructions are possible for which the numbers which define the desired elements can be obtained from the given elements (which we assumed to be represented by rational numbers) by a finite number of rational operations and extractions of square roots.

As a summary we can state the following theorem—All the numbers in the fields F_0, F_1, \dots, F_n are constructible, and conversely, any constructible number must be in one of the fields F_0, F_1, \dots, F_n . Thus, $\sqrt{3 + \sqrt[3]{2}}$ is constructible, since $\sqrt{3 + \sqrt[3]{2}}$ is in F_4 ; whereas $\sqrt{3 + \sqrt[3]{2}}$ is not constructible since $\sqrt{3 + \sqrt[3]{2}}$ is not in any one of the fields F_0, F_1, \dots, F_n .

PROBLEM SET II-B

1. Show that $7/(5 - \sqrt{2})$ is in F_1 by expressing the number in the form $a + b\sqrt{k}$, where a, b, k are in F_0 .
2. Show that $5/(2 - \sqrt[3]{3})$ is in F_2 by expressing the number in the form $a_1 + b_1\sqrt{k_1}$, where a_1, b_1, k_1 are in F_1 . Hint: To rationalize the denominator, use the identity

$$s^4 - t^4 = (s - t)(s + t)(s^2 + t^2), s = 2, t = \sqrt[3]{3}$$

We are now in a position to determine when the roots of a cubic equation are constructible, by proving the following theorem: If a cubic equation with rational coefficients has no rational root, then none of its roots is constructible. Any cubic equation with rational coefficients is said to be reducible in the field of rational numbers if it has at least one rational root. If the equation has no rational root, it is said to be irreducible in the field of rational numbers. Thus, we wish to show that no root of an irreducible cubic equation can be constructed. We can represent the cubic equation by

$$x^3 + Px^2 + qx + r = 0$$

where p, q, r are in F_0 . By hypothesis, the equation is irreducible, and consequently has no rational roots. Let us assume that one of the roots, x_1 , is constructible. Then x_1 is a number in some field F_n where n is an integer > 0 . x_1 cannot belong to F_0 , since the equation is irreducible. Let m be the smallest integer for which x_1 belongs to F_m , i.e., x_1 does not belong to F_{m-1} ($m > 1$). If the equation has any other constructible root, we assume that that root belongs to F_r , where $r \geq m$. Then x_1 is of the form

$$a_{m-1} + b_{m-1}\sqrt{k_{m-1}}$$

To simplify our notation, let

$$a = a_{m-1}, b = b_{m-1}, k = k_{m-1}$$

In other words, a, b, k belong to F_{m-1} , and $x_1 = a + b\sqrt{k}$ belongs to F_m but not to F_{m-1} .

We now show that if $a + b\sqrt{k}$ is a root of the cubic equation

$$x^3 + Px^2 + qx + r = 0$$

then $a - b\sqrt{k}$ must also be a root. If $a + b\sqrt{k}$ is a root of the equation, then

$$(a + b\sqrt{k})^3 + p(a + b\sqrt{k})^2 + q(a + b\sqrt{k}) + r = 0$$

Simplifying, we obtain

$$\begin{aligned} a^3 + 3a^2b\sqrt{k} + 3ab^2k + b^3k\sqrt{k} + pa^2 \\ + 2pab\sqrt{k} + pb^2k + qa + qb\sqrt{k} + r = 0 \end{aligned}$$

or $s + t\sqrt{k} = 0$, where

$$\begin{aligned} s = a^3 + 3ab^2k + pa^2 + pb^2k + qa \\ + r \quad \text{and} \quad t = 3a^2b + b^3k + 2pab + qb \end{aligned}$$

Thus, either $\sqrt{k} = -s/t$ or $s = 0$ and $t = 0$. However, t and s are numbers in F_{m-1} . Therefore, $\sqrt{k} = -s/t$, \sqrt{k} would also be a number in F_{m-1} , contrary to the hypothesis that m is the least integer for which x_1 belongs to F_m . Therefore, $s = 0$ and $t = 0$.

If we now substitute $a - b\sqrt{k}$ for x in the polynomial

$$x^3 + px^2 + qx + r = 0$$

we obtain the expression $s' + t'\sqrt{k}$, where $s' = a^3 + 3ab^2k + pa^2 + pb^2k + qa + r$ and $t' = -(3a^2b + b^3k + 2pab + qb)$. Thus $s' = s = 0$, and $t' = -t = 0$. Therefore, $s' + t'\sqrt{k} = 0$ and $a - b\sqrt{k}$ is a root of the cubic equation.

We now know that $x_1 = a + b\sqrt{k}$ and $x_2 = a - b\sqrt{k}$. To find the third root x_3 , we observe that the cubic equation can be written in the form

$$\begin{aligned} (x - x_1)(x - x_2)(x - x_3) = 0 \\ x^3 - (x_1 + x_2 + x_3)x^2 + (x_1x_2 + x_1x_3 + x_2x_3)x \\ - x_1x_2x_3 = 0. \end{aligned}$$

Therefore

$$x_1 + x_2 + x_3 = -p$$

or, since $x_1 + x_2 = 2a$, $x_3 = -2a - p$, which means that one of the roots, x_3 , is in the field F_{m-1} , contrary to the hypothesis that m is the least integer such that F_m contains a root of the cubic equation.

We can, therefore, conclude that if a cubic equation with rational coefficients has a constructible root, it also has a rational root. If we represent the rational root by x_r , we can write the cubic equation as

$$(x - x_r)(x^2 + p_1x + q_1) = 0$$

Consequently, the other two roots are roots of a quadratic equation and are also constructible. Conversely, if a cubic equation with rational coefficients has a rational root, we can write the equation

in the form

$$(x - x_r)(x^2 + p_1x + q_1) = 0$$

where p_1 and q_1 are rational. Thus the roots of this equation are constructible. To summarize, we can state the following theorem:

The roots of a cubic equation with rational coefficients are constructible if and only if the equation has a rational root. If the equation is irreducible, then none of its roots can be constructed with straight edge and compasses.

This property of cubic equations is basic in solving most of the construction problems the Greeks were unable to dispose of. As later chapters will show, this theorem can be used to solve the following problems—duplicating a cube, trisecting an arbitrary angle, constructing a regular polygon of 7 sides and 9 sides. The problem of squaring a circle requires results of a different nature, as the developments will show. Before we undertake the assault on these problems, there will be a brief interlude on Complex Numbers.

Finally, it is interesting to observe that the theorem on cubic equations is a special case of a more general theorem whose proof is beyond the scope of this book. We first define the term *irreducible* in a more general context: Let $p(x) = a_0x^n + a_1x^{n-1} + \dots + a_n = 0$ be a polynomial equation of degree n where n represents a positive integer and a_i represents a rational number. Then $p(x) = 0$ is reducible in the field of rational numbers if $p(x)$ can be factored into polynomials of *lower* degree with coefficients in the field of rational numbers. If $p(x)$ cannot be factored in that manner then $p(x)$ is said to be irreducible. It can now be proven that a geometric element is constructible if, and only if, the number representing the element is the root of an irreducible polynomial equation (with rational coefficients) of degree 2^k , where k represents a non-negative integer.

PROBLEM SET II-C

1. Show that $\sqrt{3 + \sqrt[4]{2}}$ is the root of an irreducible equation of degree 2^3 .
2. Construct $\sqrt{3 + \sqrt[4]{2}}$.
3. Which one of the cubic equations has a rational root
 - (a) $x^3 - 1 = 0$
 - (b) $x^3 - 2 = 0$
4. Find the three roots of the reducible cubic equation.
5. Given a cubic equation $x^3 + ax^2 + bx + c = 0$, where a , b , and c are rational numbers, and whose roots r_1 , r_2 , and r_3 are positive real numbers; if r_1 is rational, show that all the roots of the equation are constructible by showing that the roots are numbers in F_0 or F_1 . As an illustration, construct the roots of $x^3 - 7x^2 + 14x - 6 = 0$ given a unit length.
6. If $2 + \sqrt{3}$ is a root of the cubic equation $x^3 + ax^2 + bx + c = 0$, where a , b , and c are rational numbers, show that one of the roots of the equation is rational.

Complex Numbers

YOU MAY WONDER what complex numbers have to do with constructing geometric lines or figures. But as you progress you will observe that complex numbers are most useful in both algebraic and geometric problems involving real numbers.

You will recall that finding the diagonal of a square of unit side led to the equation $x^2 = 2$, and that the solution of this equation proved to be a real obstacle to the progress of Greek mathematics. The Greeks could obtain the rational numbers by forming ordered pairs of integers (a/b , $b \neq 0$). However, there was no such simple procedure for proceeding from the rationals to the reals (including irrational numbers).

Another roadblock in the history of mathematics resulted from the equation $x^2 + 1 = 0$. You should be able to prove that there is no real number x whose square is -1 . (The square of a positive or negative number is positive, and the square of 0 is 0.) There are two alternatives: either we must assume that the simple equation $x^2 + 1 = 0$ has no solution, or we must extend the real number system in such a way that the new number field will contain a solution of $x^2 + 1 = 0$. The latter alternative is, of course, the more desirable one, and the new number field can be obtained easily by following a procedure similar to that used in forming rational numbers from the integers, i.e., we form a complex number by using an ordered pair of real numbers with suitable definitions for equality, addition, and multiplication. We can represent a complex number in the form $a + bi$ ($i = \sqrt{-1}$). The definitions for equality, addition, and multiplication will be as follows:

$$1 \quad a + bi = c + di \text{ if and only if } a = c \text{ and } b = d$$

$$2 \quad (a + bi) + (c + di) = (a + c) + (b + d)i$$

$$3 \quad (a + bi) \cdot (c + di) = (ac - bd) + (ad + bc)i$$

These are the definitions you would expect if we consider i to behave as any other variable such as x with the restriction that $i^2 = -1$.

PROBLEM SET III–A

For which values of a and b will $a + bi$ be a solution of $x^2 + 1 = 0$.

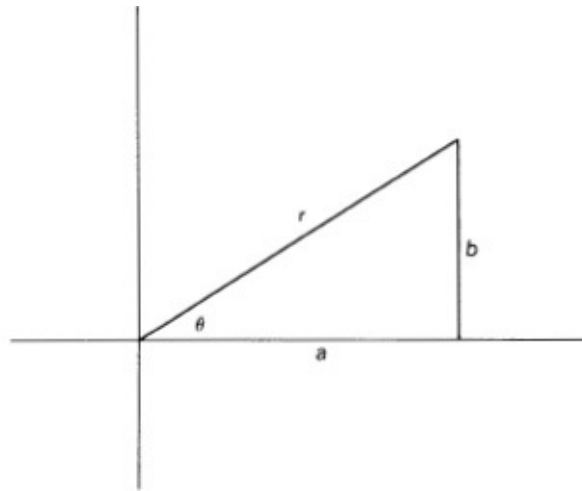
It is not necessary to use i in representing a complex number. We can merely write (a, b) , where a and b are real numbers.

PROBLEM SET III–B

1. Write the definitions for equality, addition, and multiplication, using the form (a, b) to represent a complex number.
2. If we write the additive identity for complex numbers as $(0, 0)$, and the multiplicative identity

$(1, 0)$, find the solution of $x^2 + (1, 0) = (0, 0)$ and check your answers.

You are no doubt familiar with the fact that polar coordinates (r, θ) as well as rectangular coordinates (a, b) can be used to represent a complex number. Then, in polar form, the complex number $a + bi$, or (a, b) can be represented as $r(\cos \theta + i \sin \theta)$.



The polar form of complex numbers enables us to multiply two complex numbers very easily.

$$r_1 (\cos \theta_1 + i \sin \theta_1) \cdot r_2 (\cos \theta_2 + i \sin \theta_2) \\ = r_1 r_2 [\cos (\theta_1 + \theta_2) + i \sin (\theta_1 + \theta_2)]$$

i.e., when we multiply two complex numbers we multiply the moduli and add the amplitudes.

PROBLEM SET III-C

1. Prove the last statement using the trigonometric identities

$$\sin (x + y) = \sin x \cos y + \cos x \sin y \\ \cos (x + y) = \cos x \cos y - \sin x \sin y$$

2. Prove that

$$\frac{r_1 (\cos \theta_1 + i \sin \theta_1)}{r_2 (\cos \theta_2 + i \sin \theta_2)} = \frac{r_1}{r_2} [\cos (\theta_1 - \theta_2) + i \sin (\theta_1 - \theta_2)]$$

If we let $r_1 = r_2 = 1$ and $\theta_1 = \theta_2$ we obtain

$$(\cos \theta + i \sin \theta)^2 = \cos 2\theta + i \sin 2\theta$$

The last equation is an illustration of De Moivre's theorem:

$$(\cos \theta + i \sin \theta)^m = \cos m \theta + i \sin m \theta$$

For m a positive integer, the theorem can be proven by mathematical induction. The theorem certainly holds for $m = 1$. If we assume it holds for m , then $(\cos \theta + i \sin \theta)^m = \cos m\theta + i \sin m\theta$. Therefore $(\cos \theta + i \sin \theta)^{m+1} = (\cos \theta + i \sin \theta)(\cos m\theta + i \sin m\theta) = \cos \theta \cos m\theta - \sin \theta \sin m\theta + i (\sin \theta \cos m\theta + \cos \theta \sin m\theta) = \cos (m+1)\theta + i \sin (m+1)\theta$

Thus, the theorem is shown to hold for all positive integers. However, De Moivre's theorem can be

established for all real or complex values of m . Let us use De Moivre's theorem to obtain a useful formula for *real numbers*.

If x is a real number, then $(\cos x + i \sin x)^2 = \cos 2x + i \sin 2x$. But $(\cos x + i \sin x)^2 = (\cos^2 x - \sin^2 x) + 2i \sin x \cos x$, and $\cos 2x + i \sin 2x = (\cos^2 x - \sin^2 x) + 2i \sin x \cos x$. Therefore, $\cos 2x = \cos^2 x - \sin^2 x$, and $\sin 2x = 2 \sin x \cos x$. Observe that we were able to obtain formulas involving only real numbers by equating the real and imaginary parts of two equal complex numbers.

PROBLEM SET III-D

Using the above procedure, prove

- $\cos 3x = 4 \cos^3 x - 3 \cos x$

- $\sin 3x = 3 \sin x - 4 \sin^3 x$

Hint: After equating real and imaginary parts of the complex numbers, use the relation $\sin^2 x + \cos^2 x = 1$.

Note that we shall use the first formula of [Problem Set III-D](#) when we discuss the problem of trisecting an angle.

De Moivre's theorem enables us to find the roots of unity in a very simple manner. (We shall use the roots of unity when we discuss the problem of constructing regular polygons). To find the two square roots of unity we may proceed algebraically as follows:

$$x^2 = 1 \text{ and } x = +1 \text{ or } x = -1$$

Using De Moivre's theorem we would proceed as follows: Let $R = \cos \theta + i \sin \theta$, where R is a square root of unity. Then $R^2 = \cos 2\theta + i \sin 2\theta = 1$, since R is a square root of unity. Therefore $2\theta = 2k\pi$, where k is any integer. However, only 2 values of k will give distinct values of R . Thus

$$R_1 = \cos \pi + i \sin \pi = -1 \quad (k = 1)$$

$$R_2 = \cos 2\pi + i \sin 2\pi = 1 \quad (k = 2)$$

No advantage is evident in using De Moivre's theorem in the above example. However, should we wish to find the 17 seventeenth roots of unity, then the power of De Moivre's theorem would soon become clear.

Let us try finding the three cube roots of unity. Algebraically we use the equation

$$\begin{aligned} x^3 - 1 &= 0 \\ (x - 1)(x^2 + x + 1) &= 0 \\ x_1 = 1, x_2 = \frac{-1 + \sqrt{-3}}{2}, x_3 = \frac{-1 - \sqrt{-3}}{2} \end{aligned}$$

Observe that two of the roots are imaginary numbers.

By De Moivre's theorem we have

$$R = \cos \theta + i \sin \theta$$

$$R^3 = \cos 3\theta + i \sin 3\theta = 1$$

$$3\theta = 2k\pi, k = 1, 2, 3$$

$$\theta = \frac{2k\pi}{3}, k = 1, 2, 3$$

$$R_1 = \cos \frac{2\pi}{3} + i \sin \frac{2\pi}{3}$$

$$R_2 = \cos \frac{4\pi}{3} + i \sin \frac{4\pi}{3}$$

$$R_3 = \cos \frac{6\pi}{3} + i \sin \frac{6\pi}{3} = 1$$

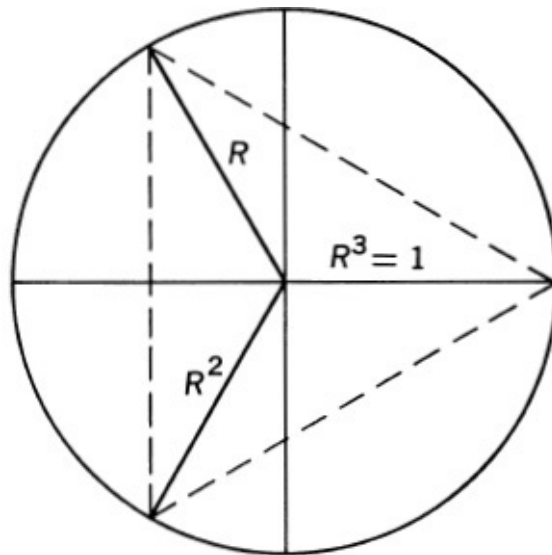
PROBLEM SET III-E

Show that $R_1 = x_2, R_2 = x_3, R_3 = x_1$.

Observe that (again using De Moivre's theorem)

$$R_2 = R_1^2, R_3 = R_1^3$$

Therefore, we can write the three cube roots of unity as R, R^2 and R^3 . Also observe that the cube roots of unity, when plotted, divide the unit circle into three equal parts and that an equilateral triangle can be formed by joining the points of division.



PROBLEM SET III-F

1. If we let $x_2 = (-1 + \sqrt{-3})/2 = \omega$, prove that $x_3 = \omega^2$ and $x_1 = \omega^3$. Does a similar relation hold for the two square roots of unity?

Let us now generalize the procedure and find expressions for the n roots of the equation $x^n = 1$ or $x^n - 1 = 0$. By using the formula for the sum of geometric series or simply by multiplying, one can show that

$$\frac{x^n - 1}{x - 1} = x^{n-1} + x^{n-2} + \dots + x + 1 \quad (x \neq 1)$$

If we let $R (\neq 1)$ be an n th root of unity, then all the roots can be expressed as $R, R^2, R^3, \dots, R^{n-1}, 1$, since an n th root of unity can be written in the form

$$\cos \frac{2k\pi}{n} + i \sin \frac{2k\pi}{n}, \quad k = 1, 2, \dots, n$$

Thus for $k = 1$,

$$R_1 = \frac{\cos 2\pi}{n} + i \sin \frac{2\pi}{n}$$

for $k = 2$,

$$R_2 = \frac{\cos 4\pi}{n} + i \sin \frac{4\pi}{n} = R_1^2$$

for $k = n$,

$$R_n = \cos 2\pi + i \sin 2\pi = R^n = 1$$

The n th roots of unity, when plotted in the complex plane, divide the unit circle into n equal arcs and joining the arcs will result in a regular n -gon. Since the roots of the equation $x^{n-1} + x^{n-2} + \dots + x + 1 = 0$ are the complex n th roots of unity and together with the root $x = 1$, divide the circle into equal parts, the equation is called the ‘‘cyclotomic’’ (circle dividing) equation. The numbers $R, R^2, \dots, R^n = 1$ form a multiplicative group since they satisfy the following four conditions:

- 1 closure $R^a \cdot R^b = R^{a+b} = R^c$, where a, b, c are integers $\leq n$
- 2 associativity $R^a(R^b \cdot R^c) = (R^a \cdot R^b) \cdot R^c = R^{a+b+c}$
- 3 identity element is R^n since $R^a \cdot R^n = R^a$
- 4 inverse element for R^a is R^{n-a}

Also observe that the inverse of R ($\cos 2\pi/n + i \sin 2\pi/n$) is R^{-1} which can be written in the form $\cos(2\pi/n) - i \sin(2\pi/n)$.

PROBLEM SET III-G

1. Express the seven 7th roots of unity ($R, R^2, \dots, R^7 = 1$) in polar form.
2. The seven 7th roots of unity form a group. Show that
 - (a) $R^3 \cdot R^6$ is a member of the group.
 - (b) The inverse of R^5 is a member of the group.
 - (c) $R^2 + (1/R^2) = 2 \cos 4\pi/7$
3. By using the formula $S = (ar^n - a)/(r - 1)$, show that

$$1 + R + R^2 + \dots + R^{n-1} = \frac{R^n - 1}{R - 1}$$

The Delian Problem

THE PROBLEM OF CONSTRUCTING a cube whose volume shall be twice that of a given cube is known as the Delian problem. D. E. Smith in his *History of Mathematics* relates the following story with reference to this problem: “. . . the Athenians appealed to the oracle at Delos to know how to stay the plague which visited their city in 430 B.C. It is said that the oracle replied that they must double in size the altar of Apollo. This altar being a cube, the problem was that of its duplication.”

The problem of duplicating a cube whose edge is one unit leads to the equation $x^3 = 2$, which is an irreducible cubic equation. For if a solution of $x^3 = 2$ were rational, then we could represent the solution by a/b , a and b integers, $b \neq 0$. Let a/b be in lowest terms, i.e., a and b have no common factor greater than 1. Then $a^3 = 2b^3$ and a^3 would be an even integer. Therefore, a would be an even integer, say $2n$, since the cube of an odd integer is odd. Thus $(2n)^3 = 2b^3$

$$b^3 = 4n^3$$

b^3 is even, and b is even, which contradicts the hypothesis that a and b have no common factor greater than 1. Since $x^3 = 2$ is an irreducible cubic equation, its roots cannot be constructed with unmarked straight edge and compasses, and it is not possible to duplicate the cube with those instruments.

Early attempts by Hippocrates and Menaechmus showed that the problem could be solved by finding the intersections of parabolas and hyperbolas. Thus the equations $x^2 = ay$ and $y^2 = bx$ result in the equation $x^3 = 2a^3$, if we let $b = 2a$.

PROBLEM SET IV–A

1. Derive the equation $x^3 = 2a^3$ from $x^2 = ay$ and $y^2 = bx$.
2. Why is this method not considered to be a “solution” of the Delian problem?
3. Show that $x^2 = ay$ and $xy = ab$, with $b = 2a$, also lead to the equation $x^3 = 2a^3$.

Diocles (second century B.C.) used the cissoid to duplicate the cube. Vieta, Descartes, Fermat, and Newton also developed methods for duplicating the cube. Newton used the limaçon of Pascal for this purpose. Of course, none of the methods were restricted to the use of unmarked straight edge and compasses.

PROBLEM SET IV–B

1. Although it is not possible to duplicate a cube, the two-dimensional analogue of the problem can be solved. Construct a square whose area is twice a given square.
2. Is it possible to construct the radius of a sphere whose surface area is twice the surface area of a given sphere?

unit sphere, or whose volume is twice the volume of a unit sphere?

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